

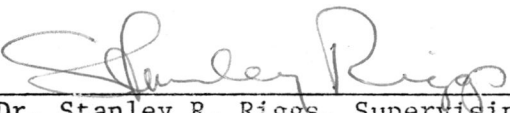
HOLOCENE EVOLUTION OF A NANOTIDAL
BRACKISH MARSH--PROTECTED BAY SYSTEM
ROANOKE ISLAND, NORTH CAROLINA

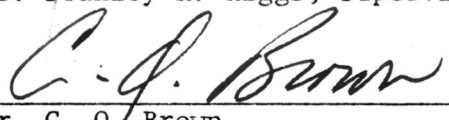
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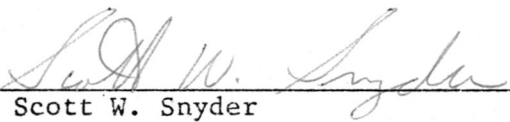
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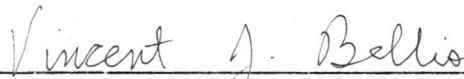
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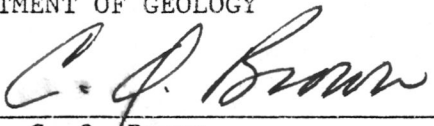

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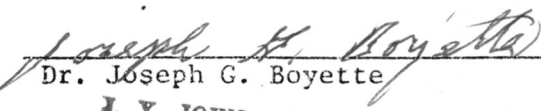

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HOLOCENE EVOLUTION OF A NANOTIDAL
BRACKISH MARSH--PROTECTED BAY SYSTEM
ROANOKE ISLAND, NORTH CAROLINA

A Thesis

Presented to

the Graduate Faculty of the Department of Geology
East Carolina University

In Partial Fulfillment

of the Requirements for the Degree
Master of Science in Geology

by

Stephen Boyd Benton

December 1979

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ABSTRACT

The Broad Creek study area on the southeastern end of Roanoke Island is located within the large estuarine system dominating the northern half of coastal North Carolina. Estuaries in northeastern North Carolina are characterized by low salinities (0 to 25 ppt) and low astronomical tides (<15 cm). However, because of their large size and shallowness, they are strongly influenced by wind tides. The study area consists of three environments; a shallow elongated embayment (Broad Creek) protected from most wave energy, a tidal creek system, and an irregularly flooded brackish marsh dominated by Juncus roemerianus.

Within the study area, sediment distribution patterns are similar to the sediment distribution patterns which occur within the larger scale estuarine system of northeastern North Carolina. Sedimentation processes operating within the study area include the following:

- 1) wave erosion during low wind tides and biocorrosion of the marsh shoreline recycling fine sediment and organic material;
- 2) permanent deposition of suspended sediments within the central, deeper portions of the bay during normal energy conditions;
- 3) deposition of suspended sediments on the marsh surface during high wind tides;
- 4) nondeposition, winnowing, and reworking of lag sands into thin shelf bars on outcrops of a muddy sand unit lateral to the central bay mud depositional environment within Broad Creek;
- 5) channel bottom scour within meanders of the tidal creek system;
- 6) deposition of highly organic rich mud on shoals lateral to the tidal creek channel; and

- 7) erosion and southerly transport of fine to medium grained sands along the high energy Roanoke Sound shoreline and deposition on a bay mouth bar forming across the southern end of Broad Creek.

Stratigraphic relationships and C_{14} dates indicate that the present Broad Creek system is a product of a series of evolutionary changes which occurred over the past 6,000 years. The study area represents a relict drainage system formed during the late Wisconsin lowstand of sea level which has been progressively drowned by rising sea level through time within an increasing influence of marine conditions. The drowning influence was confined to the floodplains from 6,000 B.P. until approximately 2,500 B.P. Between 2,500 B.P. and 1,500 B.P. fresh marshes expanded rapidly across the low interstream divides within the study area as the floodplains were overtopped by the transgression. Between 1,500 B.P. and 1,000 B.P., the fresh marshes were replaced by brackish marshes which moved into the study area from the southeast. Brackish marshes continue to dominate the study area today and respond to rising sea level by growing vertically and migrating landward over the inorganic uplands.

The Broad Creek embayment has expanded to its present size through erosion of its marsh shorelines. The eroded shorelines are undercut peat scarps with relief of 0.75 to 1.0 meter. This steplike shoreline geometry and the sedimentation processes operating within the study area represent a major departure from tidal flat shoreline geometries and sedimentation processes reported in similar scale systems characterized by astronomical tidal ranges $> \frac{1}{2}$ meter. Since this natural astronomical tidal range break falls within the microtidal classification

generally in use, a new tidal range subdivision to be called "nanotidal" is proposed for estuarine systems with a tidal range of $\leq \frac{1}{2}$ meter.

Erosional peat scarp shorelines like those found within Broad Creek are typical throughout the northeastern North Carolina estuarine system. Considering the magnitude of erosion of marsh shorelines, it is feasible that this mechanism provides a significant means of introducing organic detritus into the estuarine system where regular tidal flushing is not significant. Preliminary calculations show similar amounts of organic detritus entering the northeastern North Carolina estuaries through erosion to amounts reported entering Georgia estuaries through tidal flushing.

A C K N O W L E D G E M E N T S

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I N T R O D U C T I O N

Northeastern North Carolina is dominated by a complex of drowned river valley and bar built estuaries which cover more than 7,000 square kilometers (Figure 1). This system is the largest embayment formed behind barrier islands along the Atlantic Coast of the United States (Roelofs and Bumpus, 1953; Taylor, 1951). Though large, the estuaries are relatively shallow averaging 1.2 to 3.8 meters in depth (Roelofs and Bumpus, 1953).

Three major Piedmont draining rivers and numerous Coastal Plain rivers and streams empty into the estuarine system. Their combined drainage area of 69,000 square kilometers contributes an average annual fresh water input nearly equal to the total volume of the system (Magnuson, 1967).

The Outer Banks barrier island system separates the estuaries from the Atlantic Ocean. There are only four inlets through the barrier along the 280 kilometer stretch from Sand Bridge, Virginia to Cape Lookout, North Carolina. As a result, the estuaries are characterized by relatively low salinities, averaging 0 to 20 parts per thousand (ppt) (Jarrett, 1966; Winslow, 1887), and by very reduced astronomical tides, generally averaging 15 to 23 centimeters or less (Roelofs and Bumpus, 1953; Horton, 1967). Because of their large size and shallowness, however, they are strongly influenced by wind tides.

Much of the estuarine shoreline is bordered by brackish to fresh marsh which may range up to several kilometers wide. Wilson (1962)

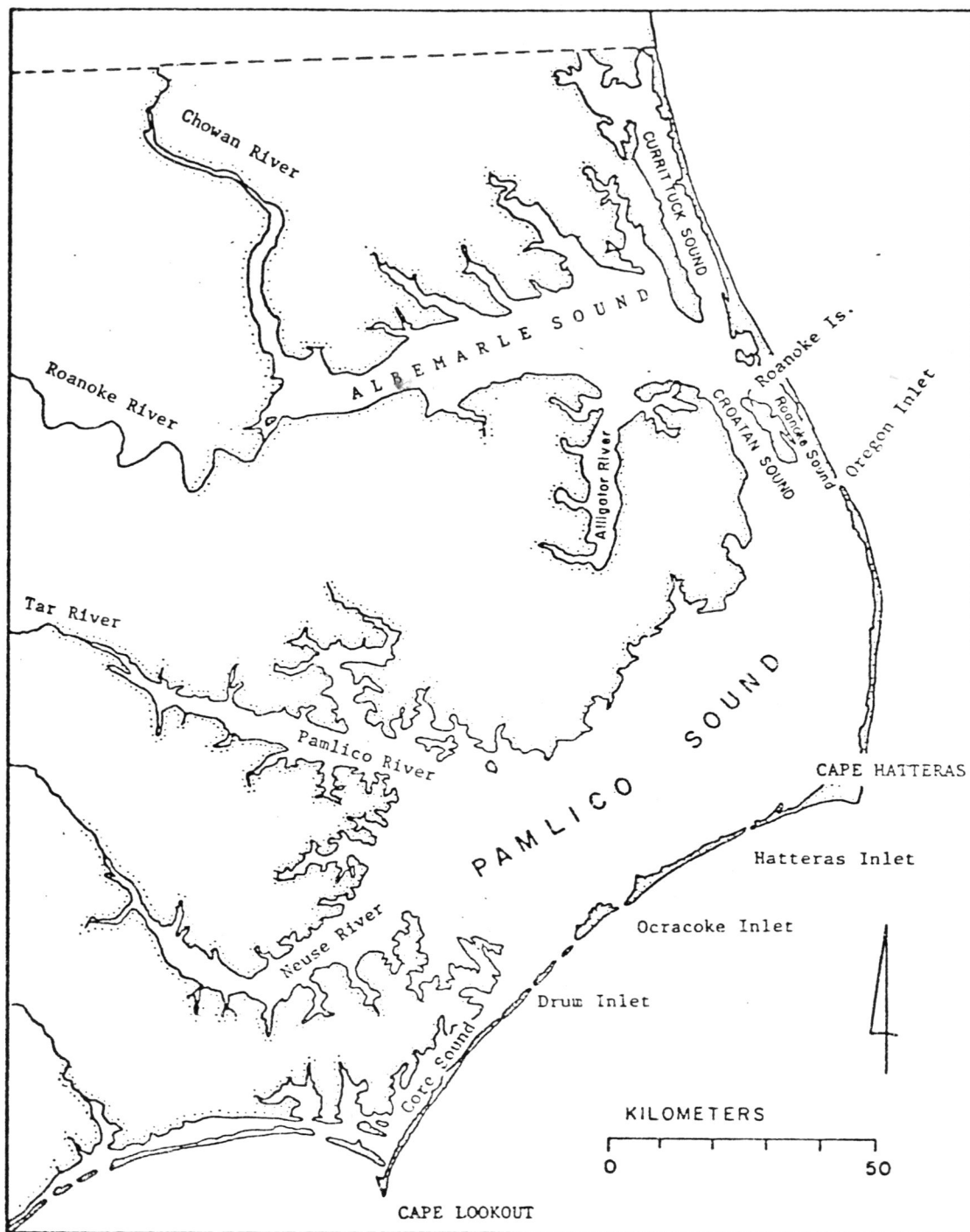


Figure 1. Northeastern North Carolina estuarine system.

reports more than 405 square kilometers of this marsh in northeastern North Carolina. Because the marshes are flooded only sporadically by wind tides rather than twice daily by astronomical tides, they are called irregularly flooded marshes.

The Broad Creek study area, located on the southeastern end of Roanoke Island (Figure 2), is an elongated embayment, tidal creek and irregularly flooded marsh system. It is protected from most significant wave energy because of its small size (700 m wide by 2,500 m long) and orientation perpendicular to the predominant winds. Broad Creek was chosen for study as a representative low energy portion of the northeastern North Carolina estuarine system and for comparison with low energy portions of estuarine systems that have a greater astronomical tidal range. The evolution of the Broad Creek system is traced through the last 6,000 years of the Holocene transgression. Particular emphasis is placed on the relative importance of modern versus relict sediment input into the system. A mechanism for introducing organic detritus into the estuarine system from irregularly flooded marshes is presented.

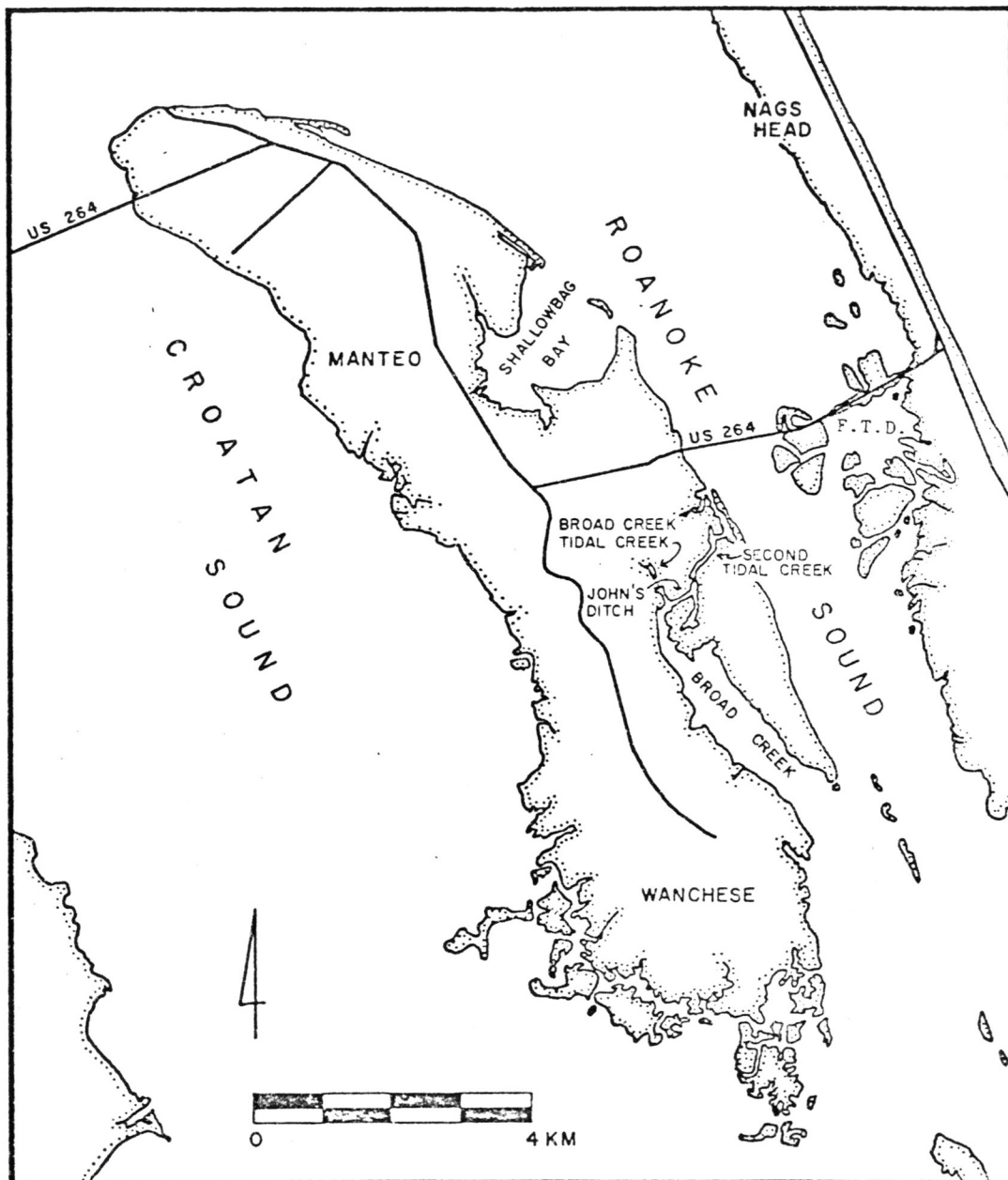


Figure 2. The Broad Creek study area on the southern end of Roanoke Island.

F.T.D.--Location of the flood tide delta of the now closed Roanoke Inlet.

ENVIRONMENTAL SETTING

Since Broad Creek is a part of the much larger northeastern North Carolina estuarine system, a brief summary of the significant environmental controls on the system is presented. The most important environmental controls include:

1. Climate, because of its influence on tides, currents and sediment influx;
2. Wind tides, because they are the dominant water level controlling factor within the system and because of their current inducing role;
3. Circulation, because of its significance on sedimentation patterns and processes;
4. Salinity, because of its influence on the plant and animal communities within the region.

Climate

Northeastern North Carolina is within the humid subtropic climatic region characterized by the alternating dominance of tropical and polar air masses. Waves of frontal high pressure air mass systems dominate the winter weather patterns. On occasion, the interaction of these air masses with associated low pressure troughs produces a counterclockwise circulation and forms a midlatitude cyclone. These storms generally travel east to northeast toward the Atlantic generating rain and winds up to 50 miles per hour which blow out of the northeast. Hence, they are locally called Northeasters.

During the summer, the subtropical convergence zone migrates north and weather patterns are dominated by the persistent Bermuda High pressure system offshore. Predominant winds are southwesterly and precipitation is more localized and intense, generally falling during convective storms. The late summer and early fall is also the season of the tropical cyclone or hurricane. The region is one of the four most frequently hit areas within North America. The probability of a hurricane occurring within a given 50 mile segment of coastline in the region during any year is 8.5 to 11% (Simpson and Lawrence, 1971).

Data from the U. S. Naval Weather Service Command Summary of Synoptic Meteorological Observations (1970) show two modal peaks in mean wind direction, N-NE and S-SW, for the offshore region. Seasonal data from the same source shows a sequential 360° shift in dominant wind direction through the year. December through March has a W-NW mode with a secondary mode in the N-NE quadrant. This period has a mean wind speed averaging 17.5 knots (32 km/hr), the yearly high. The mode shifts to the S-SW from April through August and average wind speed drops to the yearly low of 11.8 knots (22 km/hr). From September through November the modal wind direction shifts to N-NE and mean wind speeds begin to increase. E-SE wind directions are never seasonally dominant, but two secondary modes from this direction occur during the shift in major seasonal weather patterns in May and June and again in September and October.

Wind Tides

The large surface area of the northeastern North Carolina estuaries and the lack of a significant astronomical tide makes wind generated

tides the dominant water level controlling factor within the system. Normal wind tidal range is approximately 1/3 meter, but much larger ranges occur during storms. Roelofs and Bumpus (1953) concluded that a rise of nearly three meters along the windward estuarine margin opposite the maximum fetch could occur during 40 knot winds. The passage of a large storm with winds rapidly shifting to opposite quadrants can pile water up at one end of the estuary, then send it quickly against the other, significantly augmenting the tidal range. In 1933 a large passing storm produced a wind tide of 4.6 meters on the sound side of the barrier island (House Doc. 763, 1948, p. 10). The pile up of water behind the barrier in response to the wind is generally the process responsible for opening new inlets in the region.

Coates and Huneycutt¹ monitored an array of tide gauging stations along the shoreline of Croatan Sound, Roanoke Sound, and Oregon Inlet from September through October, 1971. They found that 1) high wind tides are produced by southerly winds and low wind tides are produced by northeasterly winds in the Roanoke Island area; and, 2) the tides follow wind conditions very closely, responding almost immediately to changes in velocity and direction. Coates and Huneycutt's data also suggest that, in addition to the more regional wind tide pattern, there is a local response which is related to the wind shadow effect from land bodies. Northeasterly winds produced a low tide in Croatan Sound that was approximately 0.15 meters lower on the leeward side adjacent to

¹Coates, C. L., and Huneycutt, J., 1971, Unpub. field studies, Department of Geology, East Carolina University.

Roanoke Island than on the windward western shore. Southeast winds produced a higher high tide along the windward western shore of the Croatan Sound than along its leeward shore. Roanoke Sound, which is considerably shallower and narrower than Croatan Sound, showed a north south variation in tidal range. Both high and low tides were somewhat lower in the northern portions of the sound than in the southern portions, particularly near Oregon Inlet. This appears to be related to astronomical tides moving through Oregon Inlet just to the south and to a partial restricting effect of the old Roanoke Inlet flood tidal delta that nearly bisects the sound at its midpoint.

Circulation

Currents within the northeastern North Carolina estuarine system are predominantly a function of the wind tidal system, modified to varying degrees by astronomical tides and the freshwater hydrologic head. The rivers entering the estuaries, however, are relatively small with respect to the volume of the system. Fluvial induced currents, therefore, are relatively unimportant and confined to the narrow upstream portions of the drowned river valley estuaries. The Broad Creek study area is well isolated from any potential fluvial induced current system. Currents induced by astronomical tides are confined to relatively small zones of influence adjacent to the inlets. The proximity of the study area to Oregon Inlet, however, makes astronomical tide induced currents potentially more significant to the Broad Creek system. As previously stated, astronomical tides on occasion appear to modify the effect of wind tides in Roanoke Sound near the study area. Wind

induced currents are dominant within the region and even affect astronomical tidal currents within Oregon Inlet. Roelofs and Bumpus (1953) reported a continuous ebb for two or three days as a result of strong southwest winds piling water against the backside of the barrier along the northern portion of Pamlico Sound. In general, they found that the effects of wind tides cause considerable deviation from flow predicted by standard computation methods for the inlet.

Singer and Knowles (1975) found that currents in Croatan and Roanoke Sounds are similar in intensity, roughly parallel in direction, and develop in essentially a direct response to prevailing winds. The relationship between wind direction and current direction lasts for 24 to 36 hours, but then reverses as water pileup begins a counter flow. Some reversals in current direction synchrony between Croatan and Roanoke Sounds were observed. Though southerly winds tend to produce northerly flowing currents in both, a shift to northerly winds tends to produce highly variable current directions in the northern portion of Roanoke Sound. Singer and Knowles (1975) suggested that this is caused by the constricting influence of the old Roanoke Inlet flood tidal delta in Roanoke Sound. Riggs and O'Connor (1979, pers. comm.) have also noticed this phenomena during monitoring programs, and suggest that the greater southern flow through the Croatan Sound creates a venturi effect on the Roanoke Sound water, disrupting southerly currents.

Other results of Singer and Knowles (1975) study include the following.

1. Bottom current velocities of at least 26 cm/sec were measured at all stations monitored within Roanoke and Croatan Sounds

during both northerly and southerly winds.

2. The maximum bottom current velocity measured in the Roanoke Sound was 67 cm/sec. This measurement was made in the southern portion of the Sound.
3. Basin morphology appears to have a direct modifying effect on current direction only along the shallow, narrow portion of Roanoke Sound.
4. Maximum southerly currents are stronger than maximum northerly currents in the southern portion of Roanoke Sound, while the reverse is found in the northern portion.

The present circulation pattern in the Roanoke Island area is a relatively recent development. In studying the historical shoreline and bathymetric changes in response to inlet changes, Riggs and O'Connor (1974) found that prior to the closing of Roanoke Inlet near the northern end of Roanoke Island in 1817, most of the Albemarle discharge exited through that inlet. Croatan Sound, and to some extent Roanoke Sound, were depositional in nature. Croatan Sound, in fact, was almost closed off at the southern end by marsh islands. With the closing of Roanoke Inlet and subsequent opening of Oregon Inlet to the south, the Albemarle discharge was forced through Croatan and Roanoke Sounds. Initially, both sounds were apparently erosional but by the mid 1800's the marsh islands across the Croatan Sound were eroded away and it, being the larger and deeper of the two, took over the major discharge.

Salinity

In general, the northeastern North Carolina estuarine system ranges from essentially fresh to mesohaline. Albemarle and Currituck Sounds

are the freshest because they are more isolated from a source of salty water, and because the Albemarle receives the greatest freshwater input in the region. Within the Albemarle, Bowden and Hobbie (1977) report salinities ranging from 0 ppt in the western portions of the estuary to 7 ppt in the eastern portions, though it is not uncommon for the entire Albemarle to be less than 1 to 2 ppt. The Pamlico River and the Neuse River estuaries are oligohaline, with salinity values ranging from 0.5 ppt at their western ends to highs of 20 ppt at their eastern margins (Hobbie, 1970; Hobbie and Smith, 1975). Pamlico Sound is one of the most saline estuaries in the system. Roeloffs and Bumpus (1953) report average values of 15 ppt in the western and northern portions of the Pamlico and 20 ppt in the north central area.

Salinity values in the portions of the estuary adjacent to inlets are much higher. Roelofs and Bumpus (1953) found salinities of 35 ppt adjacent to Hatteras Inlet through the entire flood tide and through nearly all the ebb tide. These high values suggest that during relatively calm periods ocean water moves into the estuaries as a homogenous mass, occupying an area of approximately 64 square kilometers just inside the inlet. During the ebb tide this mass of oceanic water remains essentially intact as it moves back out. A restricted oceanic influence is also reported at Oregon Inlet (Singer and Knowles, 1975) and Drum Inlet (Blankenship, 1976). If the behavior of the Oregon Inlet oceanic water mass is similar to that of the Hatteras Inlet water mass, Broad Creek is nearly within the geographic range of its influence.

Within the main body of the estuarine system, winds have a dominant effect on salinity distribution patterns. Because the estuaries are

so shallow, moderate winds generally keep the water column well mixed. Even the drowned river valley estuaries are generally mixed, though Hobbie (1970) reports that during particularly clam periods stratification can occur for a short time.

REGIONAL SEDIMENT PATTERNS

Estuarine Sediment Sources

Sediment deposited in estuaries is generally thought to be derived from four primary sources: 1) fluvial transportation from inland sources; 2) tidal induced transporation from oceanic water offshore; 3) erosion and redistribution of sediment from within the estuarine system; and 4) biogenic processes (Pritchard, 1952; Guilcher, 1967; O'Connor, Riggs and Winston, 1969; Meade, 1972).

Fluvial Source

The northeastern North Carolina estuaries have an average suspended sediment concentration of 17 milligrams per liter (Benton, Riggs and O'Connor, 1978), which fits into a general trend for the Atlantic Seaboard where concentrations range from a low of 4 milligrams per liter in Long Island Sound to a high of 32 milligrams per liter in the Charleston Harbor (Meade, 1972). Meade reports that this trend generally reflects the relative significance of the fluvial influence. Within North Carolina, the fact that major streams originating in the Piedmont have higher concentrations of suspended sediment than tributaries which originate in the Coastal Plain indicates that most of the suspended fluvial load originates in the Piedmont (Pevear, 1968; Benton, Riggs and O'Conner, 1978). The Tar River, one of the three major Piedmont drainage systems entering the northeastern North Carolina estuaries, has a total suspended load of 80,300 metric tons per year at Tarboro (Allen, 1965). The general lack of modern sand or coarser sized sediments at the heads of the drowned river valley estuaries indicates

that bed load is relatively insignificant along the low gradient portion of the outer Coastal Plain rivers.

Oceanic Source

The volume of sediment entering the northeastern North Carolina estuaries from oceanic sources has not been measured. The extremely limited tidal exchange, however, reduces the potential significance of an oceanic suspended sediment source. Similarly, though the clay mineralogy of the downstream portions of the estuaries suggests a non-fluvial source, these clays could be derived from local shoreline erosion rather than from an oceanic source (Hartness, 1977; Meade, 1969).

Coarse sediment distribution patterns (Pels, 1967; Pickett and Ingram, 1969; Custer and Ingram, 1974) suggest that the barrier islands, and possibly the nearshore shelf, supply a significant portion of the coarse grained sediment along the eastern margins of the estuarine system. This is introduced through eolian, overwash (Dolan, 1972), and inlet processes, with inlet processes being volumetrically dominant (Fisher, 1962; Riggs, 1976).

Internal Source

Studies by the Soil Conservation Service (1975), Bellis, Riggs, and O'Connor (1975), and Hardaway (1979, pers. comm.) indicate that estuarine shoreline erosion is a significant contributor to the estuarine sediment budget. The Soil Conservation Service reports that 182,117 metric tons of sediment per year enter the Pamlico River Estuary from the erosion of its shorelines, well over twice the yearly tonnage of

sediment contributed by its major fluvial source.

Clay mineral distribution studies (Hartness, 1977; Meade, 1969; and Pevear, 1968) suggest a decreasing fluvial influence and an increasing influence of either off shore marine sources or estuarine shoreline erosion with distance down the drowned river valley estuaries. The decreasing fluvial influence generally coincides with increasing fetch and low bank, loamy shorelines reported by Bellis, Riggs, and O'Connor (1975) to be the most rapidly eroding shoreline type. This coupled with the restricted marine influence, suggests that the clay mineral patterns are primarily the result of estuarine shoreline erosion.

Biogenic Source

Contribution to the estuarine sediment budget by flora and fauna can range from negligible to essentially 100%, depending on the influx of inorganic material and environmental conditions. Faunal contributions include production of detrital material from the breakup of hard skeletal or shell material and the filtration of very fine suspended particles by clams, oysters (Haven, 1970), and polychaete worms (O'Connor, Riggs and Winston, 1969). Filtered fine grained material is then excreted as larger aggregated fecal pellets, which settle more readily and are incorporated into the bottom sediments. The significance of filtration within North Carolina's estuaries has not been quantified.

Shell fragments are reported in measurable percentages within the sediments of most of the environments within the region, but there appears to be a general increase as the marine influence increases. Pels (1967) reports Rangia cuneata shells in all the environments within the fresher portions of Albemarle Sound. Oyster shells and

oyster dominated shell hash are reported in the eastern Albemarle Sound (Pels, 1967), Croatan and Roanoke Sounds (Riggs and O'Connor, 1974), and Pamlico Sound (Pickett and Ingram, 1969). Shell hash is found in the highest concentrations within Pamlico Sound where Pickett and Ingram (1969) report that it makes up 20% of the inlet associated sediments, 15% of the central channel muds at the mouth of the Pamlico River where it occurs as shell hash layers, 12% of the central basin muds where it also occurs as layers, and up to 9% of the sediments in other environments described.

Floral contributions to the estuarine sediment budget can be either allochthonous, material washed in from upstream or from adjacent source areas, or autochthonous, accumulation through in place growth. Autochthonous contributions generally occur where the proper energy conditions permit marsh systems to prograde out into the estuarine system, as described by Redfield (1967, 1972) in the Barnstable marshes of New England. Significant progradation does not occur in northeastern North Carolina because marsh shorelines are generally erosional (Soil Conservation Service, 1975; Bellis, Riggs and O'Connor, 1975). If, however, the irregularly flooded marshes adjacent to the estuaries are considered a part of the estuarine system, they represent a significant component (405 sq km) that is dominated by autochthonous, biogenic deposition.

Most of the combustable organic material reported in the sediments (4% in the Pamlico Sound, Pickett, 1965; 13% in the Pamlico River, Hartness, 1977; and 16% in the lateral embayments studied by Duque, 1978) is thought to be allochthonous plant material carried into the estuary from swamp forests upstream and from adjacent marshes. Biochemical

analysis of sediments from two bays in the Pamlico Sound area by Berryhill, Swanson, and Love (1972) showed a high alkaline-soluble humic fraction and a low bitumen content, indicating a large plant relative to animal contribution to the total organic fraction.

It appears that the origin of the sediments within the north-eastern North Carolina estuarine system is dominantly internal. Most of the inorganic fraction is derived from the erosion of shorelines, though approximately one third of the silts and clays are presently being introduced into the system primarily by Piedmont draining rivers. Autochthonous organic accumulation is also significant on the irregularly flooded marshes within the region. Oceanic sources appear to be localized in influence limited primarily to barrier island processes.

Sediment Distribution Patterns

Drowned River Valley Estuaries

Pels (1967) divided the Albemarle Sound into several sedimentary environments on the basis of grain size associations, lithology, benthic organisms and bathymetric characteristics. Three environments dominated the embayment; a broad featureless "bay center," a relatively steeply dipping "bay slope" which borders on the bay center, and a relatively flat "bay shelf" between the bay slope and the shoreline.

Of the three, the bay center environment encompasses the largest area and extends nearly the entire length of the Albemarle Sound. Water depths range from 9.0 meters in the middle to approximately 3.6 meters near shore. Sediments are silty clays that rarely contain

any grains larger than very fine sand. Organic material and relatively high percentages of mica and heavy minerals are common constituents.

The bay slope, which forms a relatively narrow border around the bay center, is slightly coarser grained. Clayey and sandy silt is the dominant sediment on the slope, which ranges from 1.8 to 3.6 meters deep. Organic material is "plentiful"; mica and heavy minerals are present but are not as abundant as in the bay center.

The bay shelf, another relatively flat surface, extends from the upper edge of the bay slope to the shore. Sediment patterns are variable, particularly grain size, but sediments are generally coarser toward shore. Clays and silts are generally absent from the bay shelf and shoreline sediments.

Hartness (1977) found a similar sediment distribution and bottom morphology pattern in the Pamlico River estuary to the south. Three dimensional analysis of the central muddy basin showed that an ancient river valley has been filled with silts and clays that are as much as 20 meters thick at its confluence with Pamlico Sound. Organic concentrations within the muds are variable but generally increase up the estuary and lateral tributaries. Clay mineralogy suggests a dominantly fluvial source in the upper portion of the estuary and a locally eroding shoreline or oceanic source for downstream sediments.

Duque (1978) studied two small lateral embayed creeks off the Neuse River estuary. A similar pattern of finer grain sizes toward the center was observed. Bottom sediments are dominantly a dark brown to black, slightly sandy, organic-rich mud underlain by a relatively hard sandy substrate. The organic percentage averages 16% by weight and increases upstream.

Bar Built Estuaries

Sediment distribution patterns in the Pamlico Sound (Pickett and Ingram, 1969) are similar to those in drowned river valley estuaries in that the finest units are found in the deeper central basins (5.5 to 7.3 m). Silts and clays with some very fine sand and shell fragment layers are the dominant sediment types in the central basins. Sand percentages generally increase toward the margins. Central basin muds within the Pamlico Sound bar built estuary generally have lower clay percentages and higher silt percentages than the drowned river valley central bay muds.

Surrounding the central basins and comprising the largest area is the marginal lagoon environment. Marginal lagoon sediments on the mainland side of the central basins are silty fine sands. Sediments on the barrier island side, however, are cleaner, coarser grained, and more closely related to the barrier island sediments. Barrier island and inlet shoal sediments are generally clean, medium sized sands with relatively high percentages of heavy minerals.

Superimposed upon the mainland side marginal lagoon sediments are a series of large finger shoals oriented perpendicular to the shore. Lithologically, they are similar to the marginal lagoon sediments except that the fines are absent, apparently from the winnowing action of waves and currents. Their association with entering streams and rivers suggests that they are related to fluvial depositional processes during a lower sea level stand.

The rest of the environments identified by Pickett and Ingram (1969) are associated with and related to the shorelines. Bottom

sediments have higher percentages of organic material adjacent to marsh shorelines. Sediments within protected embayments have high percentages of clays and silts. Along sandy mainland beach systems, the sediment appears to be related to a local erosional source, such as the reworking of Pleistocene beach features along Cedar Island.

Pickett and Ingram (1969) found the Croatan Sound to be a complex scoured system exposing what they interpret as relict bottom sediments. Detailed studies which included shallow cores by O'Connor, Riggs, and Winston (1972) and Riggs and O'Connor (1974) of the Croatan Sound verified the relict nature of the bottom sediments. Two relict units, a lower transgressive sandy marine unit and an overlying regressive fluvial gravelly sand are exposed within the deeper scoured channels of the Croatan Sound.

Generally, the bottom sediment distribution pattern of Croatan Sound is similar to the other estuaries in the region in its relationship to the bathymetry. Modern, very fine sands and organic rich muds are found in deeper less turbulent areas along with the relict clayey sediments. Fine sand is the dominant bottom sediment type. Medium, coarse, and gravelly sands are also found but appear to be related to the erosion of relict units along the deeper channels of the Croatan Sound and the shorelines of Roanoke Island.

Riggs and O'Connor (1974) found that fine sand is particularly abundant in Roanoke Sound. This is apparently due to the active eolian, washover, and inlet sedimentation processes which have been operating in the recent past. Some muds were reported, however, within the narrow shipping channel which runs down the western side of the sound.

REGIONAL STRATIGRAPHY

Within the study region, the upper 65 meters of the thick sediment pile overlying the crystalline rock basement is Plio-Pleistocene (Brown, Miller, and Swain, 1972). Detailed studies of the upper 18 meters of the section (Riggs and O'Connor, pers. comm.) revealed a consistent three part stratigraphy spanning the past 40,000+ years.

The basal unit is a very fossiliferous, muddy sand with C₁₄ dates between 24,500 and 40,000 years B.P. Fossils include Venericardia sp., Mercenaria sp., Arca sp., Crepidula sp., and abundant Mulinia lateralis. The unit exhibits lateral facies variations that indicate low to moderate energy marine environments.

Overlying the "Mulinia" bed is a middle section of regressive, fluvial, or possibly deltaic, gravelly sand. Detailed acoustic sub-bottom profiling revealed a relatively extensive series of buried channels, some of which appear to be related to the middle units, oriented approximately perpendicular to the coast. Tops of the channels average 5 meters below sea level and their bases reach depths of -16 to -17 meters. Generally the channels are asymmetric showing southward migration (steep side) and progradational fill from the north.

Also associated with either the middle unit or basal unit is a medium to coarse, fossiliferous sand with abraded fragments of Mercenaria sp., Mactra sp., Nassarius sp., and Mulinia sp., suggesting a high energy barrier island or shoal environment. This facies makes up the backbone of Roanoke Island. It is also found along the mainland shoreline of Croatan Sound where it appears to be laterally related to a relict lagoonal facies to the west. The interpretation of Roanoke Island as a

barrier island is also supported by the drill hole data of Pierce and Colquhoun (1970).

The upper units include the Holocene transgressive barrier island sands and beach gravels, estuarine muddy sands, marsh peats, and south trending channel fill muds characterized by an assemblage dominated by Cyrtopleura costata and Tagelus plebeius. The north-south trending systems appear to be related to shifting hydraulic patterns in response to the opening and closing of inlets, a process which has been documented in historic times. C_{14} dates from this unit suggest that this process has been going on for at least 2,140 years.

A hiatus that separates the upper units from the middle and lower units indicates that the region was exposed to subaerial erosion during the late Wisconsin lowstand of sea level approximately 18,000 years ago, (O'Connor and Riggs, 1974). Iron staining appears to have been wide spread during this time as a result of pedogenesis.

SYSTEM EVOLUTION

Regional

Subsurface data from the region indicate that the northeastern North Carolina estuarine system is undergoing an orderly evolutionary sequence through the Holocene sea level rise. This sequence as outlined by Riggs and O'Connor (1975) involves four major processes:

- 1) migration upward and landward of the barrier island over the eastern margin of the estuarine system;
- 2) flooding of lowlands adjacent to estuaries producing vertical accumulation of marsh peats;
- 3) erosion of estuarine shorelines allowing them to maintain their size;
- 4) deposition of fluvial and estuarine shoreline derived sediments as blanket sands and silts along the flooded trunk estuaries, while suspended sediments are deposited in the perimeter marshes and low energy, deep central bays and lateral tributaries.

As the present transgression continues the whole system will migrate westward across the Coastal Plain.

A drowning evolutionary system is usually a large scale process involving major drainage basins, such as the Neuse River, Pamlico River and Albemarle Sound system of North Carolina (Riggs and O'Connor, 1975) or the Delaware River Bay system (Kraft, 1971). Submergence occurs primarily along major trunk and lateral streams. On a small scale, however, the lateral lagoon and protected embayment portions of these systems tend to fill through tidal flat processes and are converted to marsh (Kraft, Sheridan, Moose, Strom and Weil, 1974).

Broad Creek

Broad Creek is a small scale component of the northeastern North Carolina estuarine system. Preliminary reconnaissance of the embayment, however, did not reveal any obvious filling or tidal flat development, so two working hypotheses on the origin and evolution of the study area were considered:

- 1) a gradual cutoff of Broad Creek from Roanoke Sound by spit progradation along what is now the marsh peninsula separating the two sounds, a small scale process; or,
- 2) the gradual drowning of a paleodrainage system, a large scale process.

The first hypothesis is similar to the origin of Barnstable Harbor and its associated marsh system in Massachusetts (Redfield, 1959, 1965, 1972). Barnstable Harbor began to be cut off from Cape Cod Bay approximately 3,000 years ago by a prograding spit. The protection from wave energy provided by this spit allowed development of tidal flats, which were colonized by Spartina alterniflora as the flats built up to the critical elevation. At first, this process was confined to relatively narrow strips along the basin shoreline. As the spit continued to prograde, affording greater protection from wave energy to larger areas, the flats and their associated marshes spread into the bay. This process is continuing today as nearly half of the bay is filled with tidal flats and marsh.

The general stratigraphic sequence produced by the spit process with the original embayment is tidal flat sands overlain by a relatively thin layer of intertidal peat which is overlain by high marsh peat. As sea

level has risen approximately 6 meters since the onset of spit, bay, and marsh formation, the marsh has also prograded over the surrounding uplands. This process produces a stratigraphic sequence of soil overlain by high marsh peat. A distinctive, organic unit geometry is produced by the combined processes. The thickest peat accumulations are found in areas where the fringing marshes first developed along the bay margin. Peat units gradually thin as their basal elevation increases both toward the bay center and inland over the buried uplands.

A drowned paleodrainage system should exhibit a dissected paleosol base overlain by fresh water units which would be overlain by units that indicate increasing marine influence. The greatest thicknesses of organic accumulation should be found within the ancient trunk streams, if it is not eroded away during the transgression.

M E T H O D S

Field

A base station for field operations was established at the East Carolina University Institute of Coastal and Marine Resources Marine Science Center at Manteo, North Carolina. Reconnaissance, bottom sampling, and coring within the study area was done from the Institute's 14 foot skiff and the East Carolina University Geology Department's 25 foot coring barge, "Old Tom."

Station Establishment

Twenty-seven shore stations were established around the perimeter of Broad Creek. Each was marked with a flagged two meter pole visible from the opposite shoreline. Each station was located on 1" = 200' aerial photo base maps obtained from the Dare County Tax Office. A series of traverses (Figure 3) were made between the stations with a Raytheon DE 725 continuous recording fathometer in order to 1) observe the general bathymetric features within the Broad Creek system and 2) to make a preliminary sample requirement determination. Approximately 1/3 of the traverses were rerun in the opposite direction to reduce wind and current drift effects on the bathymetric map and station locations tied to bottom features.

Probe Traverses

A series of probing traverses across the marsh were made from the shore stations along ditch alignments or compass bearings to determine peat thickness and relief on the underlying inorganic units. Coring in

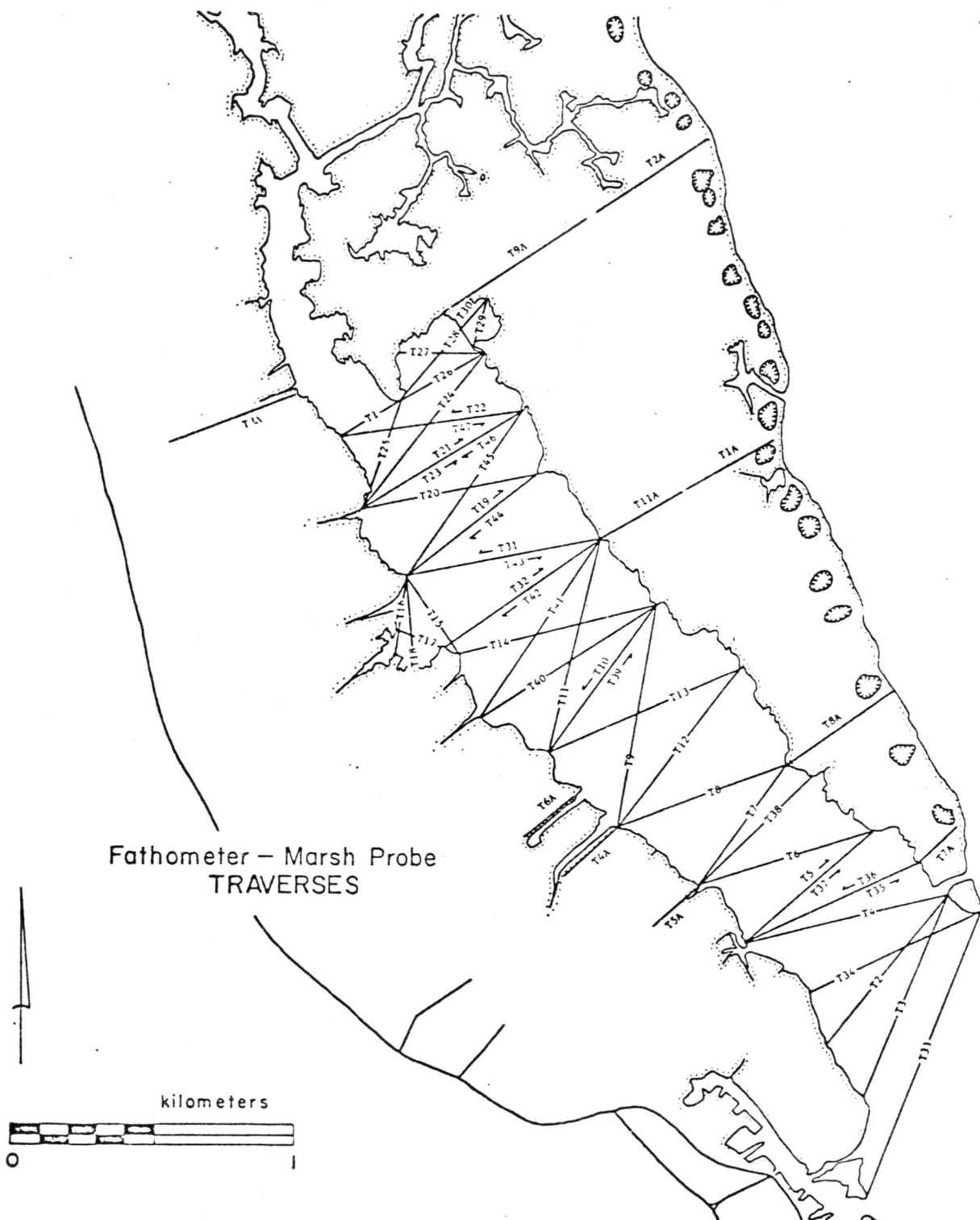


Figure 3.

conjunction with probes indicated that the accuracy of probe measurements was limited to approximately 0.5 meters as a result of variable penetration into the underlying inorganic units.

Surface Sampling

Bottom sediment reconnaissance and sampling was conducted by SCUBA or snorkel diving along the traverses established within the embayment. Bottom sampling stations (Figure 4) were selected to provide areal coverage of the embayment and to define features observed on fathometer traverses. Bottom reconnaissance generally included a description of the 1) bottom sediment, 2) sedimentary features, 3) wave and current energy conditions, 4) organisms present, and 5) the underlying sediments where a diver could dig through the surface sediments.

Subaerial reconnaissance and sampling was conducted along the marsh probe traverses and at the shore stations. This included observations on 1) vegetation types and zonation patterns 2) shoreline morphology 3) peat thickness 4) organisms present and 5) sediment types.

Core Sampling

Coring within the study area (Figure 5) was done by driving three inch diameter PVC irrigation pipe into the substrate from the coring barge or, on dry land, with the aid of a portable 15 foot tripod and hand operated well driver (Figure 6 and 7). The core was retained in the core pipe during extraction by filling the core pipe extending above the substrate with water, and sealing the top with a plumber's test plug. Compaction was checked prior to removal of the core from the

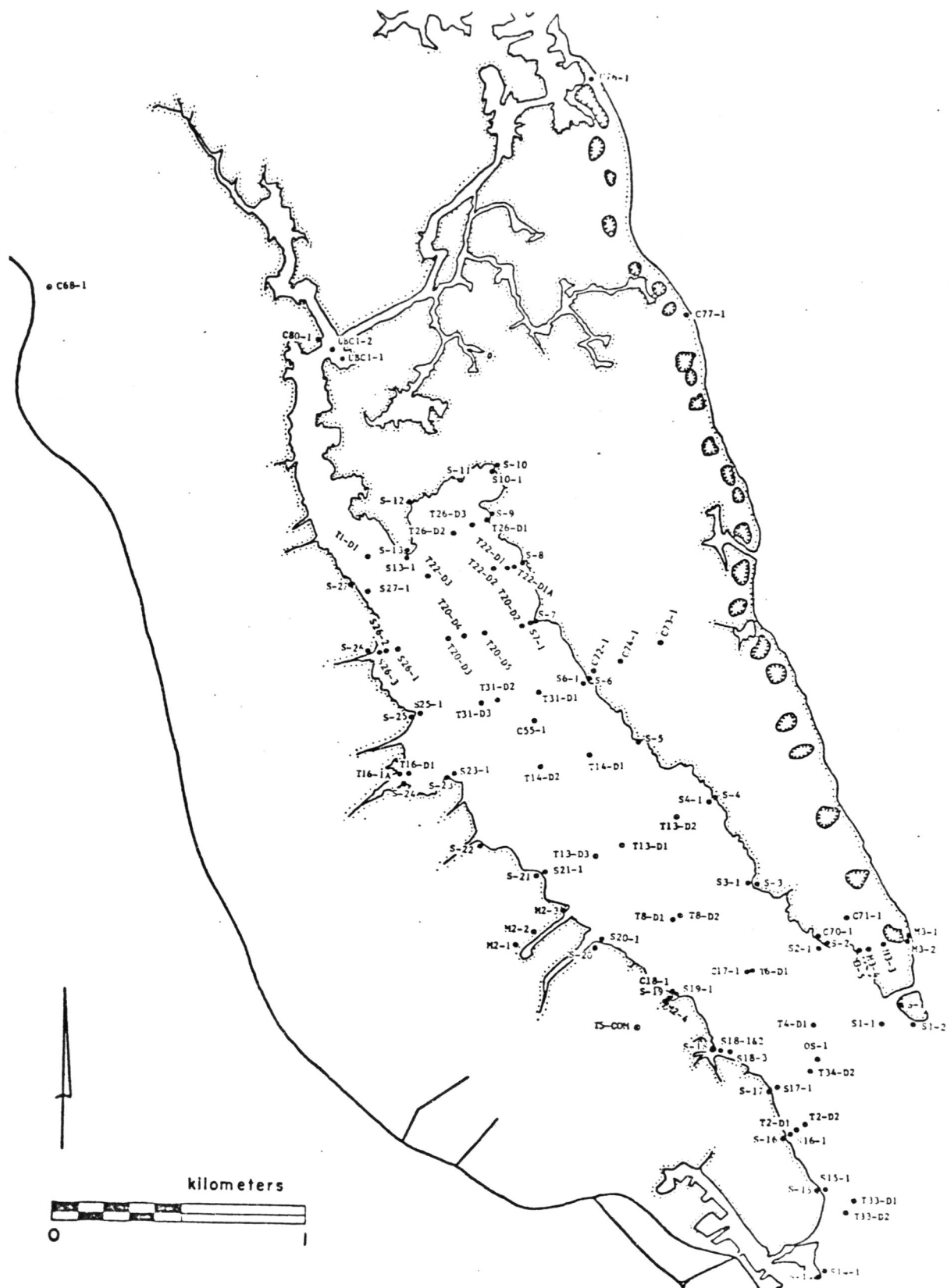


Figure 4. Bottom sample station locations.

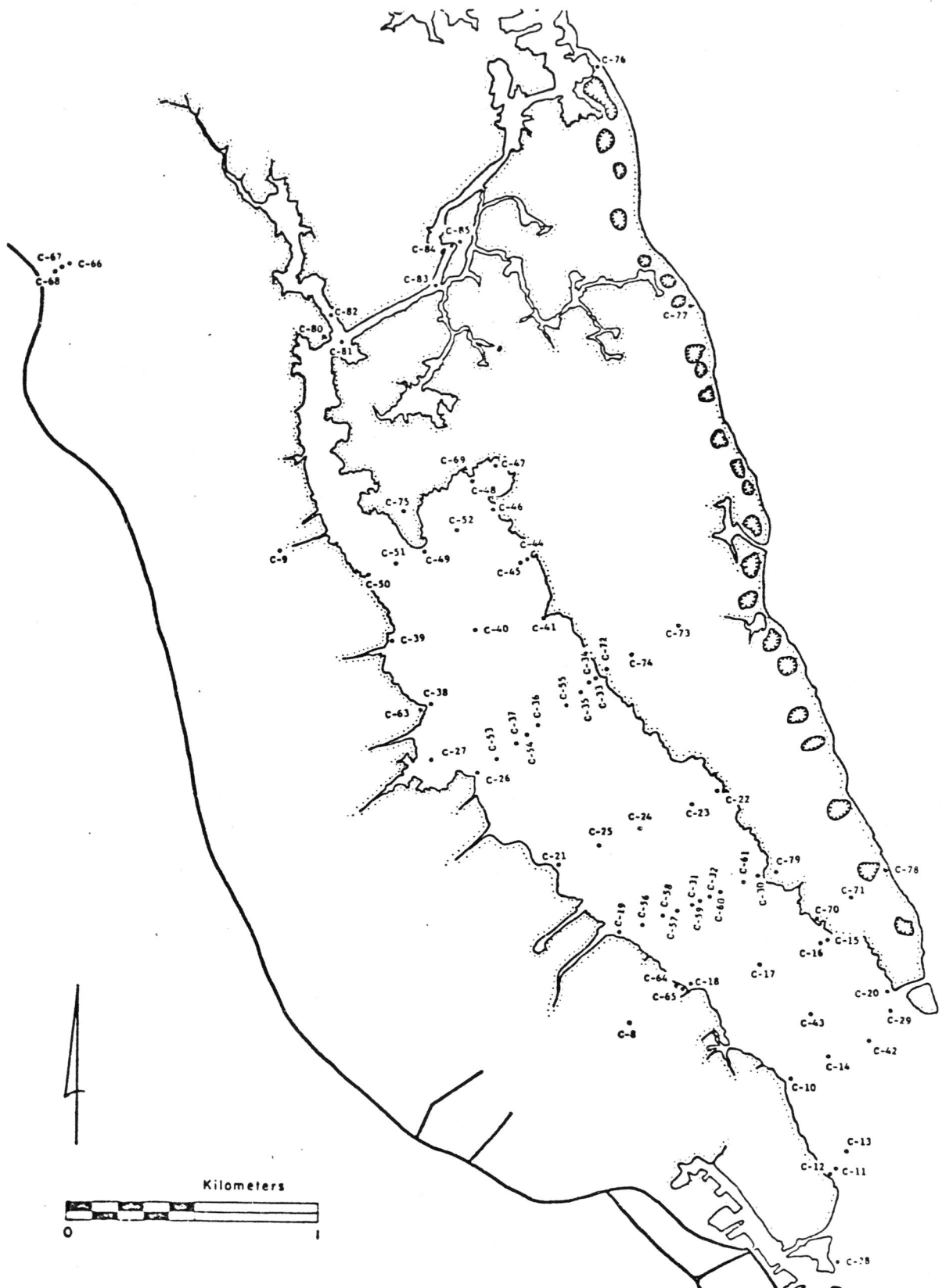


Figure 5. Core locations.



Figure 6. Removing a land core. Notice the plumers test plug sealing the top of the core barrel.



Figure 7. A freshly extruded core. The cores were extruded into plastic lined two meter wooden carriages for transport from the field.

substrate and uniformly averaged through compactable units within a given core. Compaction, however, was not found to be a serious problem and rarely approached 20%.

Suspended Sediment Sampling

Water samples for suspended sediment concentration determination were collected in a pole mounted wide mouth jar sealed with a rubber stopper. When the jar was lowered to the desired sampling depth, the water sample was collected by pulling a string attached to the rubber stopper. The samples were stored in 500 milliliter amber water bottles and frozen until processed in the lab.

Laboratory

Sample Preparation

Each core was split lengthwise, described, and divided into general lithologic units. A quartersplit of the core was then broken into samples 30 centimeters or less in length on the basis of lithology. One hundred twenty representative samples from 22 cores and 85 surface grab samples were selected for more detailed sedimentological analysis. These samples were split into ± 70 gram subsamples, soaked in 5% calgon solution for 24 hours, and wetsieved through a 63 micron sieve to determine the weight percent fine fraction ($>4 \phi$ or <63 microns).

Coarse Fraction Studies

The coarse fraction ($<4 \phi$ or >63 microns) was processed optically using a method modified after Ingram (1965). Sorting values for the

coarse fraction were determined with the aid of comparators published by Fold (1968), and Beard and Weyl (1973). Eleven samples were Ro-Tapped through one-half ϕ sieves for 10 minutes to check the accuracy of the optical techniques for grain size and sorting determination. Modal grain size determination showed no difference between the two techniques. Optical sorting results were the same, or within one category of the sorting determined statistically from the Ro-Tapped samples. Coarse fraction parameters determined optically include:

Inorganic components

- 1) Dominant grain size
- 2) Maximum grain size
- 3) Sorting
- 4) Rounding - fine to medium grains
- 5) Rounding - coarse grains
- 6) Frosting - fine to medium grains
- 7) Frosting - coarse grains
- 8) Volume % Fe stained grains
- 9) Volume % non-quartz minerals
- 10) Dominant non-quartz minerals
- 11) Accessory non-quartz minerals

Organic components

- 12) Volume % plant material
- 13) Volume % fragile shell hash
- 14) Volume % robust shell hash
- 15) Presence or absence of foraminifera

Constituent plant species could usually be identified optically in peat samples collected from the living root zone (upper 20 cm). However, peat from below this zone was generally too degraded to be identifiable without utilizing peat petrology techniques. The plant material in all of the samples could readily be broken into relative percentages of 1) fine fragments of grassy vascular and epidermal tissue, 2) dark amorphous aggregates, 3) wood, and 4) the presence or absence of seeds. This information was sufficient to differentiate between the three major peat producing marsh types found within the region.

Suspended Sediment Studies

Suspended sediment water samples were thawed and split into ± 100 milliliter samples with a microsplitter. The volume was measured to the nearest 0.5 milliliter in a graduated volumetric flask. The samples were then vacuum filtered through pre-dried and weighed 0.45 micron Millipore filters, dried 12 hours in a vacuum oven at 70°C, and stored in dessicators to cool in groups of four. To avoid weight gain problems during handling, all weighing was done in a dehumidified room and all filters were re-weighed in the same order that they had been initially weighed. In addition, three control filters with dummy distilled water samples were processed with the sediment samples.

C₁₄ Sample Preparation

The peat and wood samples chosen for C₁₄ dating were examined for contamination under a binocular microscope. All suspected modern root or other contaminants visible were removed prior to shipping the samples to Teledyne Isotope's radiocarbon laboratory. At the lab, the samples were further treated for the removal of carbonates, humic acids, and visible mold. The shell dated was treated with successive acid washes to remove the outer 12%. A Libby half-life of 4468 years was used to calculate the ages. No corrections have been applied to the data.

P H Y S I C A L C O N D I T I O N S

W I T H I N B R O A D C R E E K

Salinity, tidal flux, and wave characteristics were observed on an intermittent basis to gain some general baseline data. A systematic study of physical conditions was beyond the scope of the present study. Most of the data collected represent normal energy conditions during the relatively low energy summer season. Data collected during the fall also represents normal energy conditions because of the difficulty of working during high energy events.

Salinity

Salinity values were determined with a Goldberg refractometer on 12 randomly selected dates. Three of these sample sets provide coverage of the entire study area over a short time period, and one included a series of measurements at established stations over a 24-hour period. Other sample sets represent spot checks during other field operations.

Surface salinities ranged from 5.5 ppt to 14.3 ppt in Broad Creek, Bottom values were generally somewhat higher, ranging from 7.2 ppt to 16.5 ppt. The mean surface salinity for all sample sets was 10.1 ppt, which splits the range of 5 to 15 ppt reported by Singer and Knowles (1975) for the Roanoke Sound region.

Salinity values obtained during the diurnal sample set are summarized in Table 1. Four generalizations can be made from the data:

- 1) Differences of 10.5 ppt occurred between surface and bottom salinity values at the mid bay stations revealing surprising stratification for a shallow, "well mixed" estuary.

TABLE 1. DIRUNAL SALINITY MEASUREMENTS

Southern Broad Creek			T6-D1 Center			West Bank		East Bank	
Salinity ppt									
Time	Wind (knots)	Tide (cm)	Surf	Bottom		Surface	Bottom	Surface	Bottom
2:00 PM	SE 0-5	0	7.2	14.3	7.2	7.2	7.7	8.8	8.8
3:00 PM	SE 0-5	---	6.6	16.5	10.0	---	---	---	---
4:00 PM	E-NE 0-5	-5	7.2	16.5	9.3	7.7	9.4	7.2	8.3
6:00 PM	SE 5-10	0	7.7	16.5	8.8	7.7	8.8	8.3	9.4
8:00 PM	Calm	+2.5	8.3	15.4	7.1	7.2	10.5	7.2	7.2
9:00 PM	Calm	+5	7.2	15.4	8.2	---	---	---	---
10:00 PM	Calm	---	5.5	16.0	10.5	---	---	---	---
12:00	Calm	---	6.6	14.3	7.7	---	---	---	---
2:00 AM	Calm	---	7.2	13.8	6.6	---	---	---	---
6:00 AM	Calm	+7.5	7.2	12.7	5.5	7.2	8.8	7.2	7.2
10:00 AM	NE 0-5	+7.5	8.8	16.0	7.2	8.8	9.4	8.8	8.8

Northern Broad Creek			T20-D4 Center			West Bank		East Bank	
Time	Wind	Tide	Surf	Bottom		Surface	Bottom	Surface	Bottom
6:00 PM	SE 5-10	0	7.2	11.0	3.8	6.6	7.7	8.3	9.4
7:00 PM	Calm	---	6.6	10.5	3.9	---	---	---	---
8:00 PM	Calm	+2.5	6.6	11.0	4.4	---	---	---	---

- 2) During calm periods, the bottom salinities peaked at 12 hour intervals, three hours after high tide at Oregon Inlet.
- 3) A southeast wind at 0-5 knots apparently also produced a bottom salinity peak.
- 4) The bottom salinity peaks had no apparent relationship to water level fluctuation.

The data indicate that relatively homogeneous bodies of saline water move slowly into Broad Creek. Apparently these water masses are driven by astronomical and wind tides, or a combination of both. Degradation of these water masses is relatively slow in the deeper central portions of Broad Creek and appears to be more rapid along its margins.

Waves

Because of the small size of Broad Creek and its isolation from larger bodies of water, most of the waves are internally generated capillary and small amplitude, shallow gravity waves. The southern portion of the bay is exposed to the greatest fetch and generally has the largest waves. These include waves migrating in from the larger Roanoke Sound, particularly during periods of southerly winds. A large shoal at the mouth of Broad Creek, however, reduces the size of waves within the bay. The largest waves recorded were approximately one-third meter in height.

Tidal Flux

A tide gauge was placed on a fixed channel buoy at the mouth of Broad Creek. Normal water level was established during a calm period which lasted several days.

During the summer sampling periods water level fluctuations generally ranged from 8 to 15 centimeters. However, the flux commonly was zero if the weather was stable. No astronomical tidal fluctuations were detected.

A much greater water level flux was observed during the fall, even though only fair weather weekend trips to the study site were made. Water level values ranged from -46 to +15 centimeters, though a shift of this magnitude was not observed during any single visit to the site.

Sustained southwest winds over 15 knots produce high wind tides of +15 centimeters or more within Broad Creek. At this level, the entire marsh, with the exception of the levees and Spartina patens zones, is covered with water approximately 8 centimeters deep. These high wind tides were observed to last as long as three days.

Suspended Sediment

The water column in Broad Creek is turbid. Visibility was never more than approximately 1½ meters during the bottom reconnaissance and sampling dives, which is typical for the region. Turbidity generally increases and the water contains more particulate and dissolved organic matter towards the shorelines and up the tidal creeks.

A set of thirty-nine 100 milliliter water samples was collected from a sample grid within Broad Creek, the tidal creek, and Roanoke Sound

(Figure 8). During the two week period preceding the sampling date in August, no significant storms had affected the study area and the wind speeds were within the long term August average. Salinity values, measured as the water samples were collected, averaged 10.1 ppt which is equal to the mean overall Broad Creek value. Splits of the water samples were filtered through .45 micron preweighed filters, and the suspended sediment concentration was reported as milligrams per liter.

Suspended sediment concentration patterns are summarized in Table 2. At the time the sampling was conducted, Broad Creek suspended sediment concentrations averaged 20 to 25 milligrams per liter, 5 to 10 milligrams per liter higher than Roanoke Sound except at WC 34, the northernmost sampling station. The higher sediment concentration and lower salinity value at station 34 suggests that a fresher, muddier water mass was within Roanoke Sound just to the north of the study area. Suspended sediment concentrations down the center of Broad Creek averaged 5 milligrams per liter less than the sides. Mean values along both shorelines were similar to one another in spite of southwest winds producing greater wave energy along the eastern shore.

The suspended sediment concentrations within Broad Creek were higher than expected, particularly considering the relatively calm weather conditions during sampling. In a year long study of suspended sediments, Benton, Riggs, and O'Connor (1978) reported mean suspended sediment concentrations of less than 15 milligrams per liter in northeastern North Carolina's three drowned river valley estuaries for the same time period. In addition, the suspended sediment concentrations in these major estuaries generally decrease downstream away from the major fluvial influence. Similarities between Broad Creek and

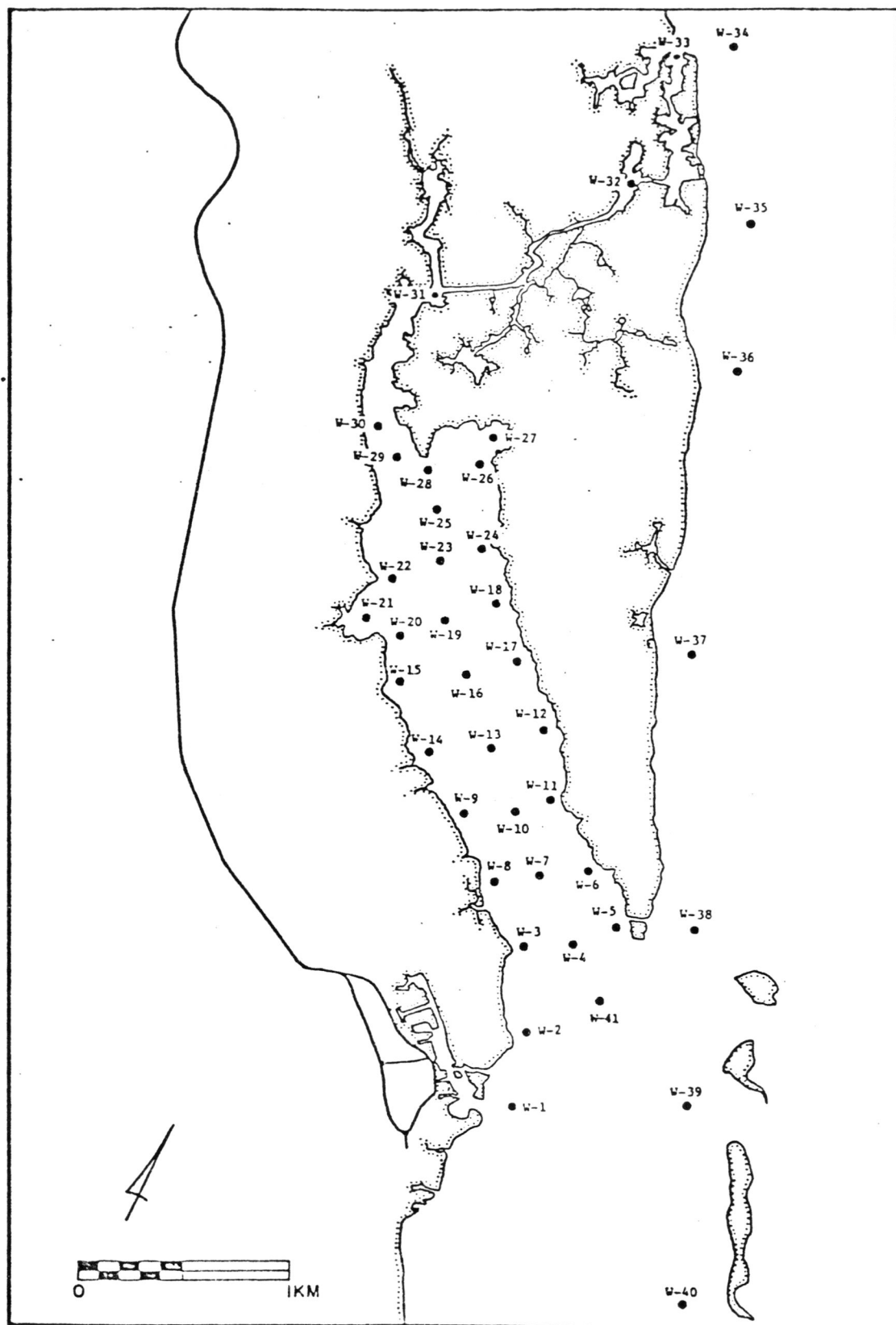


Figure 8. Suspended sediment sampling stations.

TABLE 2. SUSPENDED SEDIMENTS

Broad Creek West Shore Stations			Broad Creek Center Stations			Broad Creek East Shore Stations		
Sta. no.	Suspended Sediment Conc. mg/l	Salinity ppt	Sta. no.	Suspended Sediment Conc. mg/l	Salinity ppt	Sta. no.	Suspended Sediment Conc. mg/l	Salinity ppt
W-29	28.4	9.4	W-28	21.9	8.8	W-27	16.1	8.8
W-22	26.2	10.5	W-25	17.0	9.9	W-26	35.7	9.4
W-21	21.2	11.6	W-23	28.0	9.4	W-24	15.3	9.4
W-20	40.7	10.5	W-19	5.0	9.9	W-18	10.4	9.9
W-15	27.1	11.0	W-16	26.4	9.9	W-17	29.1	9.9
W-14	2.5	11.0	W-13	37.9	9.4	W-12	33.7	10.5
W-9	29.3	11.0	W-10	-	9.9	W-11	40.4	10.5
W-8	29.5	10.5	W-7	33.0	10.5	W-6	20.0	10.0
W-3	28.0	11.0	W-4	4.9	10.5	W-5	32.0	11.0
W-2	-	10.5	W-41	7.0	9.4			
W-1	29.0	11.0						
Range	2.5-40.7	9.4-11.6	Range	4.0-37.9	8.8-10.	Range	10.4-40.4	8.8-11.0
x	26.19	10.72	x	20.02	9.76	x	25.85	9.93
Sd.	9.62	.55	Sd.	12.53	0.52	Sd.	10.59	0.67
Cv.	37%	5%	Cv.	63%	5%	Cv.	41%	7%

Tidal Creek

Sta. no.	Suspended Sediment Conc. mg/l	Salinity ppt
W-33	15.1	9.9
W-32	20.7	11.0
W-31	31.1	9.9
W-30	22.9	9.4
Range	15.1-31.1	9.4-11.0
x	18.7	10.05
Sd.	13.18	0.67
Cv.	70%	7%

Roanoke Sound

Sta. no.	Suspended Sediment Conc. mg/l	Salinity ppt
W-34	27.9	9.4
W-35	15.9	10.5
W-36	8.1	11.0
W-37	14.5	11.0
W-38	11.2	11.0
W-39	12.4	11.0
W-40	25.6	11.0
Range	8.1-27.9	9.4-11.0
x	16.51	10.7
Sd.	7.44	0.60
Cv.	45%	6%

the drowned river valley estuaries are the decreasing concentrations of suspended sediment away from the shorelines and a lack of apparent areal relationships between suspended sediment concentration and salinity.

MODERN SEDIMENTARY ENVIRONMENTS

Broad Creek Embayment

Broad Creek is a relatively flat bottomed bay averaging 1.5 meters in depth with undercut erosional scarps along the shorelines and a poorly defined central channel slightly over 2 meters deep. Water depth at the shore ranges from 0.72 to 1.0 meter (Figure 9). Four major sedimentary environments, which are closely related to the bathymetry, can be distinguished: 1) a central basin; 2) bay shelves; 3) shelf bars; and, 4) a bay mouth bar. In addition, erosion of the marsh shoreline bordering the embayment has left a narrow (1 to 5 m wide) peat bench on the bay bottom along much of the shoreline. Also a subaqueous highly organic rich mud shoal, more typical of environments found within the tidal creek system, is developed within the small embayment off the northeastern portion of Broad Creek (Figure 10).

Central Basin

The central basin is a relatively flat feature extending nearly the full length of the bay. To the south it is cut off by the bay mouth bar and to the north it gradually becomes more shallow and loses its distinctiveness.

The central basin is characterized by a mud bottom which is commonly greater than one meter thick. The mud is thickest in the southern half of Broad Creek and gradually thins to one meter or less toward the northern half. The mud also thins and becomes more sandy laterally.

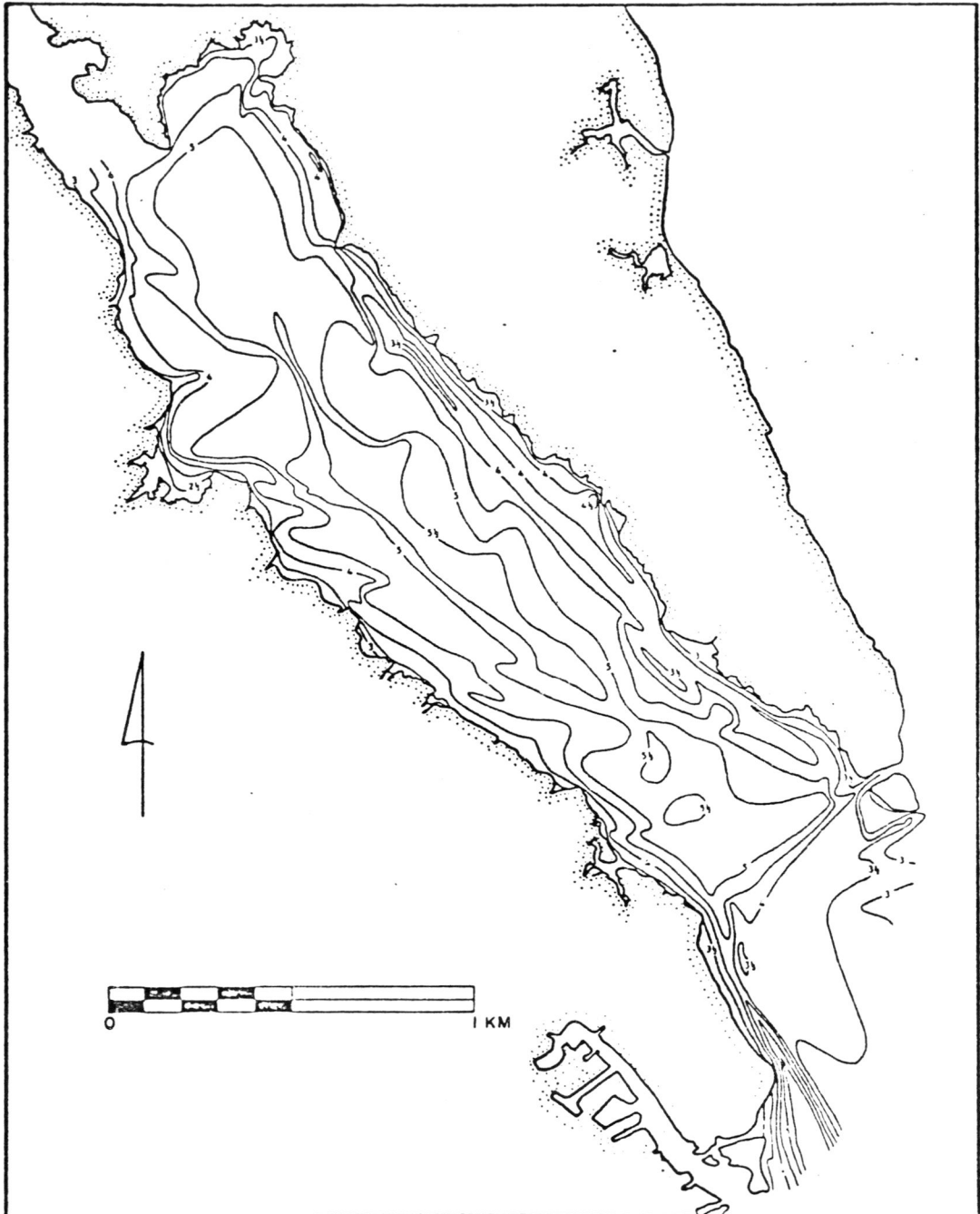


Figure 9. Broad Creek embayment bathymetry. Contours are drawn at $\frac{1}{2}$ foot intervals.

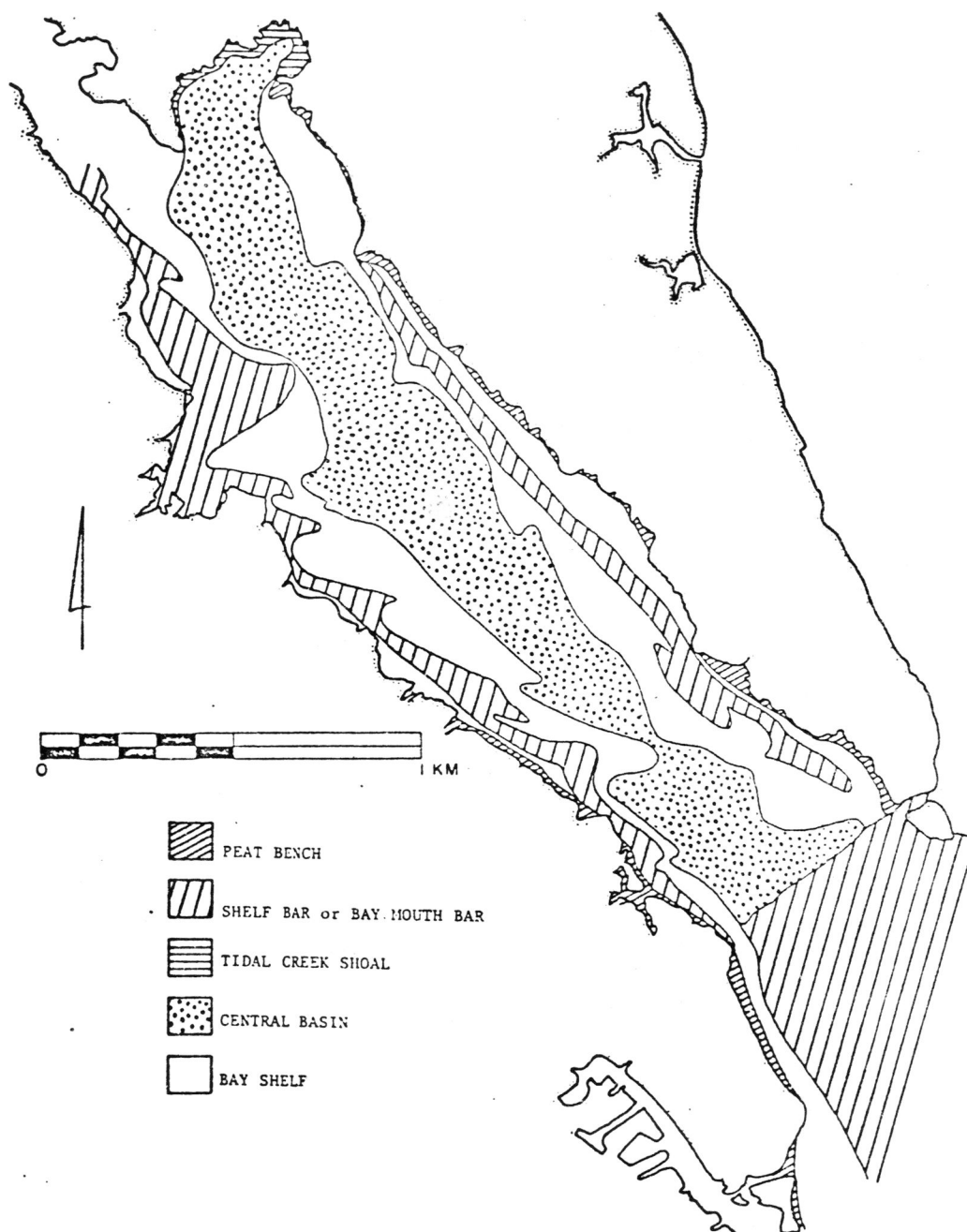


Figure 10. Broad Creek embayment sedimentary environments.

Muds from the central basin (Table 3) average 75% silt and clay by weight. The silt and clay percentage generally increases both upstream within the basin and toward the central portions of the environment, away from the bay shelf. The coarse fraction is characterized by very fine to fine grained, moderately well sorted quartz sand. Mica, commonly a green degraded variety, is the dominant accessory mineral but it rarely makes up 5% by volume of the coarse fraction. Other accessory minerals include opaque heavy minerals and occasionally glauconite (14% of the samples contained trace amounts of this mineral). Plant material averages 23% by volume of the coarse fraction and is dominated by fine fragments of vascular and epidermal material. The central basin mud samples also contain relatively high percentages ($\bar{X}$ =12% of the organic fraction) of wood fragments. All of the samples contain at least trace amounts of fragile shell hash. No evidence of wave or current energy within this environment was observed during reconnaissance or sample collecting dives during the relatively low energy summer field period. In fact, the surficial centimeter of the mud is characteristically a thin skim of organic-rich mud that is easily suspended by the slightest motion of the diver.

Polychaete worms, with their characteristic burrows surrounded by fecal and pseudofecal mounds were the dominant benthic macroscopic organisms observed living in the central basin environment. An occasional live Mulinia lateralis was observed; however, most found were dead. Only dead specimens of Tagelus plebius, Cryptopleura costata, and Crassostrea virginica were found.

TABLE 3. CENTRAL BASIN SAMPLE SUMMARY

NO. SAMPLES: 14	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂		
FINE FRACTION ($>4\phi$)								
Weight %	33%-93%	75%	18.9	25%	91-100%	29%	71-80%	21%
COARSE FRACTION ($<4\phi$)								
Dominant Grain Size	V.Fine-Fine	V. Fine	0.4	24%	Fine	79%	0-10%	21%
Maximum Grain Size	Med.-Gran.	V.Coarse	1.1	17%	V. Coarse	36%		
Sorting	V.Well-Poor	M.Well	1.5	28%	M.Well	29%	Well	29%
% Fe Stained	0-1%	85%	0.4	43%				
Volume % Plant Material	7-50%	23%	14.9	65%	11-20%	36%	0-10%	29%
Fine Grassy Fragments	T-99%	70%	34.8	50%	91-100%	36%	81-90%	21%
Dark Aggregates	T-55%	18%	20.8	116%	0-10%	64%	31-40%	21%
Wood	0-50%	12%	15.5	129%	0-10%	71%	11-20%	14%
Seeds	0-10%							
Dominant Non-Quartz Mineral	Mica (93% of spls.)							
Secondary Non-Quartz Minerals	Mica (100%), Glauconite (14%), Opaque Heavies (71% of spls.)							
Fragile Shell Hash	T-7%							
Robust Shell Hash	0%							
Foraminifera	One Sample Had Milioline Forms							

Bay Shelves

Flanking the central basin along both sides of Broad Creek are the bay shelves. A slight increase in slope separates these shelves from the central basin. However, the maximum relief on the slopes is less than one-third meter. The somewhat irregular bay shelves form a series of lobes extending toward the central basin.

Bottom sediments on the bay shelves are typically a cohesive, light tan, muddy sand. During the summer field season these sands are overlain by a thin, easily disturbed layer of organic-rich mud similar to the central basin surface layer. Commonly, particularly within the southern half of the bay, the surface of the muddy sand is pocked by burrows backfilled with clean sand or mud. Tree trunks, logs and other woody debris are occasionally found on the bay shelf, especially in the southwestern and northeastern areas of the bay.

The results of laboratory analysis of samples from the bay shelf are summarized in Table 4. Silt and clay averages 24% by weight of the bay shelf muddy sand unit. The coarse fraction is either poorly sorted or moderately well sorted, fine to medium grained quartz sand. Most poorly sorted samples are from the southern one-third of the study area. The moderately well sorted samples are from the more protected, somewhat lower energy, upstream portions of the bay. Accessory minerals range from a trace to one to two percent of the coarse fraction and are dominantly opaque heavy minerals. Most samples also contain trace amounts of mica.

Plant material averages 15% by volume of the coarse fraction and is mostly fine fragments of grassy vascular and epidermal tissue. In some of the samples, fragments are recognizable as Juncus roemerianus. Both

TABLE 4. BAY SHELF SAMPLE SUMMARY

NO. SAMPLES: 14	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂
FINE FRACTION (>4φ)						
Weight %	17%-42%	24%	7.5	31%	11-20%	43% 1-30% 36%
COARSE FRACTION (<4φ)						
Dominant Grain Size	Fine-Med.	U.Fine	1.0	40%	Fine	69% L.Med. 15%
Maximum Grain Size	Coarse-Pebble	V.Coarse	1.0	15%	Coarse	31% V.Coarse 31%
Sorting	V.Poor-Well	Mod.	1.7	42%	M.Well	39% Poor 23%
% Fe Stained	T-10%	3%	3.0	105%		
Volume % Plant Material	2-35%	15%	11.8	80%	0-10%	50% 11-20% 29%
Fine Grassy Fragments	45-99%	87%	18.8	22%	91-100%	62% 61-70% 15%
Dark Aggregates	0-45%	8%	13.7	163%	0-10%	77%
Wood	0-30%	5%	8.3	153%	0-10%	92%
Seeds	Three Samples Had Trace %					
Dominant Non-Quartz Mineral	Opaque Heavy Minerals (93% of spls.)					
Secondary Non-Quartz Minerals	Mica (77%), Fe Agg. (23%), Glauconite (8% of spls.)					
Fragile Shell Hash	0-1%	0.4%	0.4%	94%		
Robust Shell Hash	0-4%	0.7%	1.50%	200%		
Foraminifera	One Sample Had Planispirally Coiled Forms					

fragile and robust shell hash is common in the samples. The bay shelf is the only environment in which robust shell hash was detected in the sediment samples. It is also the only submarine environment in which planispirally coiled foraminifera were found.

Four samples from the southwestern bay shelf and from a narrow channel into the southern portion of the Broad Creek embayment are distinctly different from the typical bay shelf sediment type. This portion of the bay shelf is characterized by a high concentration of logs, stumps, and other woody debris. The sediment is a relatively clean, slightly gravelly, iron stained quartz sand (See Appendix 2). Aside from the large pieces of woody debris, this sediment has a lower organic content than the typical bay shelf muddy sand.

The dominant macroscopic organisms living on the bay shelves are polychaete worms. This environment, however, appears to be somewhat more diverse than the central basin, at least on the surface. The sediment surface is covered with numerous shallow depressions 8 to 15 centimeters in diameter. The origin of these features is unknown. Living and dead oysters are commonly found scattered on the bay shelves. No reef bioherms were observed, nor were any organisms found producing the burrows found in this environment backfilled with mud or sand.

Shelf Bars

Superimposed on the higher portions of the bay shelves are a series of low (less than one-third meter) shoals or bars which are distinguishable on fathometer traverses and aerial photos (Figure 11). The shelf bars on the western bay shelf are larger than those on the eastern shelf



Figure 11. Shelf bars within the Broad Creek embayment. Bars are faintly visible as light areas adjacent to the western shoreline of the bay. (From ERTS-1 imagery dated October 25, 1965.)

and generally parallel the geometry of the bay shelf. Bars on the eastern bay shelf form linear features parallel to the shore and perpendicular to the lobes of the shelf.

The results of laboratory analysis of shelf bar sediments are shown in Table 5. Shelf bar sediments are moderately well sorted, fine grained quartz sand. Accessory minerals include opaque heavy minerals and mica. Silt and clay averages only 6% by weight of those samples wet sieved and plant material averages only 3% by volume of the coarse fraction. Samples having more than a trace amount of organic plant material are generally located close to the shore. Most of the samples contain at least trace amounts of fragile shell hash and over 20% contain milioline foraminifera.

Shelf bar sands normally overlie the muddy sand of the bay shelf. However, within the small embayment off the northwestern section of Broad Creek, between stations 23 and 25, the shelf bar overlies mud and peat.

No ripples or other evidence of sediment movement were observed during the summer reconnaissance or sample collection dives on the bars. The bars were coated with the same easily disturbed, thin, organic-rich mud layer found in the central basin and bay shelf environments.

Polychaete worms and oysters are the dominant organisms observed. Polychaete worms are again dominant while oysters are noticeably less abundant than they are on the bay shelves.

Bay Mouth Bar

The mouth of Broad Creek is almost closed by a broad bay mouth bar which extends south and west from the southern tip of the peninsula

TABLE 5. SHELF BAR SAMPLE SUMMARY

NO. SAMPLES: 14	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂
FINE FRACTION (>4ϕ)						
Weight %	2%-11%	6%	2.6	44%	0-10%	93% 11-20% 7%
COARSE FRACTION (<4ϕ)						
Dominant Grain Size	Fine-Med.	U.Fine	1.3	46%	Fine	72% Med. 21%
Maximum Grain Size	Med.-Pebble	V. Coarse	1.4	20%	Gran.	29%
Sorting	V.Poor-V.Well	M.Well	2.0	43%	M.Well	36% Well 21%
% Fe Stained	T-10%	2%	2.9	135%	0-10%	100%
Volume % Plant Material	T-10%	3%	3.7	114%	0-10%	100%
Fine Grassy Fragments	20-100%	76%	25.4	34%	91-100%	36% 71-80% 21%
Dark Aggregates	0-80%	14%	21.2	148%	0-10%	64% 11-20% 21%
Wood	0-35%	10%	12.3	122%	0-10%	72% 31-40% 14%
Seeds	One Sample Had Trace %					
Dominant Non-Quartz Mineral	Opaque Heavy Minerals (100% of spls.)					
Secondary Non-Quartz Minerals	Mica (64%), Glauconite (7% of spls.)					
Fragile Shell Hash	0-1%	T%				
Robust Shell Hash	One Sample Had 1%					
Foraminifera	Three Samples Had Milioline Forms					

separating Broad Creek from Roanoke Sound. Access to Broad Creek is limited to a narrow channel adjacent to the western shoreline of the bay. Superimposed on the shoal are a series of low relief megaripples distinguishable on aerial photos (Figure 12). Laboratory analyses, Table 6, indicate that the bay mouth bar sands are slightly less muddy and contain less plant material than the shelf bars. Similar percentages of fragile shell hash and milioline foraminifera are found in both environments.

Degraded ripples were observed during dives on the shallower ($< \frac{1}{2}$ m) areas of the bar. The absence of the thin, surficial organic-rich mud layer suggests that the bay mouth bar is a relatively high energy environment. The large ripples which show up on the 1965 aerial photos were not observed during this study, suggesting a fairly active and changeable system.

The dominant benthic organisms observed were polychaete worms. Shallow depressions were also common and an occasional blue crab was encountered. Oysters were absent during the field study even though the bar was an oyster lease area.

Tidal Creeks

The upstream portion of Broad Creek consists of two separate tidal creek systems characterized by irregularly embayed shorelines. These tidal creek systems have been connected by John's Ditch, a canal dug by slave labor prior to the Civil War (Figure 13). The circulation pattern provided by John's Ditch may have a major influence on the present bathymetry of the tidal creek system.

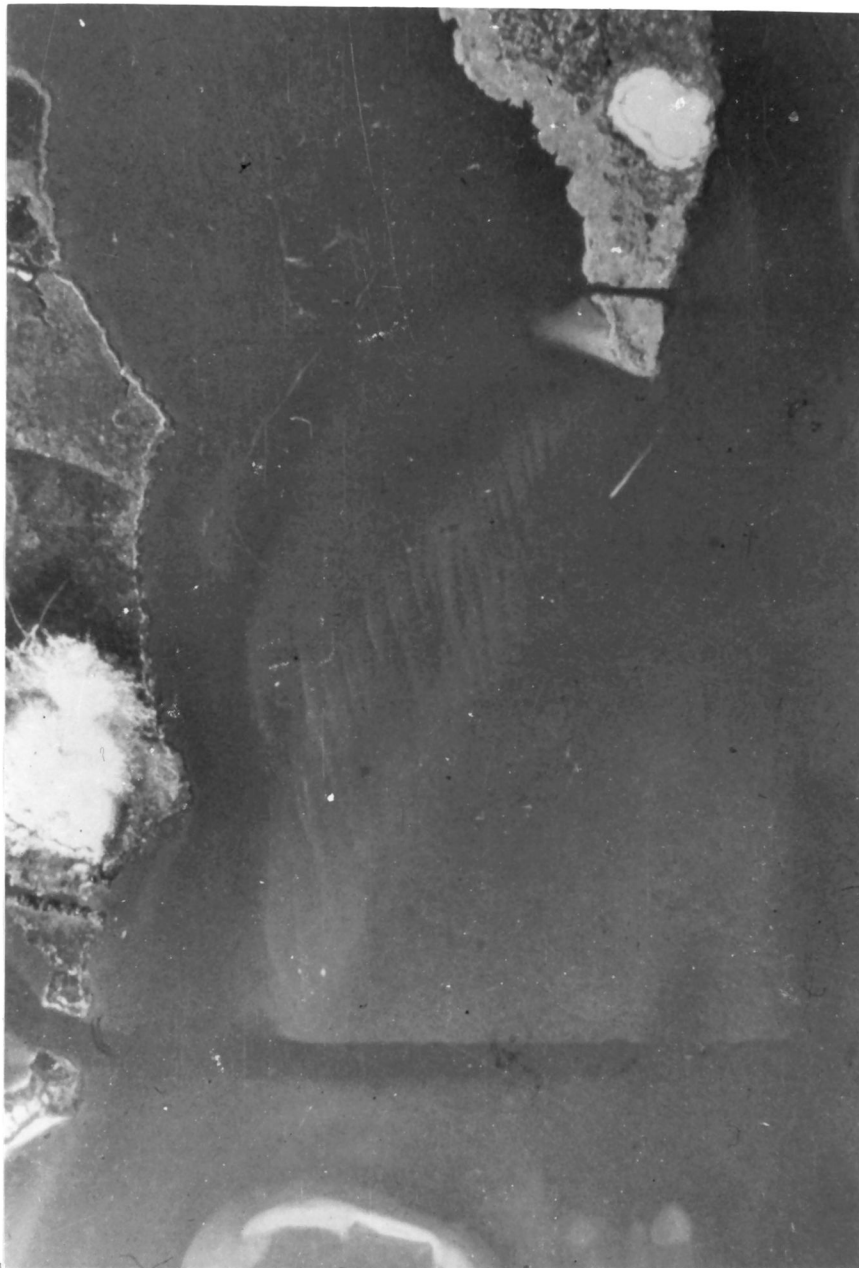


Figure 12. Bay mouth bar at the southern end of the study area. Note the megaripples superimposed on the bar surface. The dark horizontal band near the bottom of the photo is a dredged channel connecting Wanchese Harbor with the Roanoke Sound. (From ERTS-1 imagery dated October 25, 1965.)

TABLE 6. BAY MOUTH BAR SAMPLE SUMMARY

NO. SAMPLES: 6	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂
FINE FRACTION ($>4\phi$)						
Weight %	1-6%	3%	1.9	69%	0-10%	100%
COARSE FRACTION ($<4\phi$)						
Dominant Grain Size	U.Fine-Med.	L.Med.	1.3	32%	Med.	50%
Maximum Grain Size	Coarse-Gran.	Gran.	0.8	11%	Gran.	67%
Sorting	Poor-Well	Mod.	1.5	39%	M.Poor	33% Mod. 33%
% Fe Stained	T-20%	7%	7.2	101%	0-10%	83%
Volume % Plant Material	0-1%	0.4	0.4	88%	0-10%	100%
Fine Grassy Fragments	99-100%	99%	0.5	0.5%	91-100%	100%
Dark Aggregates	0-1%	0.5%	0.4	82%		
Wood	0-0.5%	0.3%	0.3	112%		
Seeds	0%					
Dominant Non-Quartz Mineral	Opaque Heavy Minerals (100% of spls.)					
Secondary Non-Quartz Minerals	Mica (67%), Glauconite (17% of spls.)					
Fragile Shell Hash	All Spls. Had Trace %					
Robust Shell Hash	0%					
Foraminifera	One Sample Had Milioline Forms					

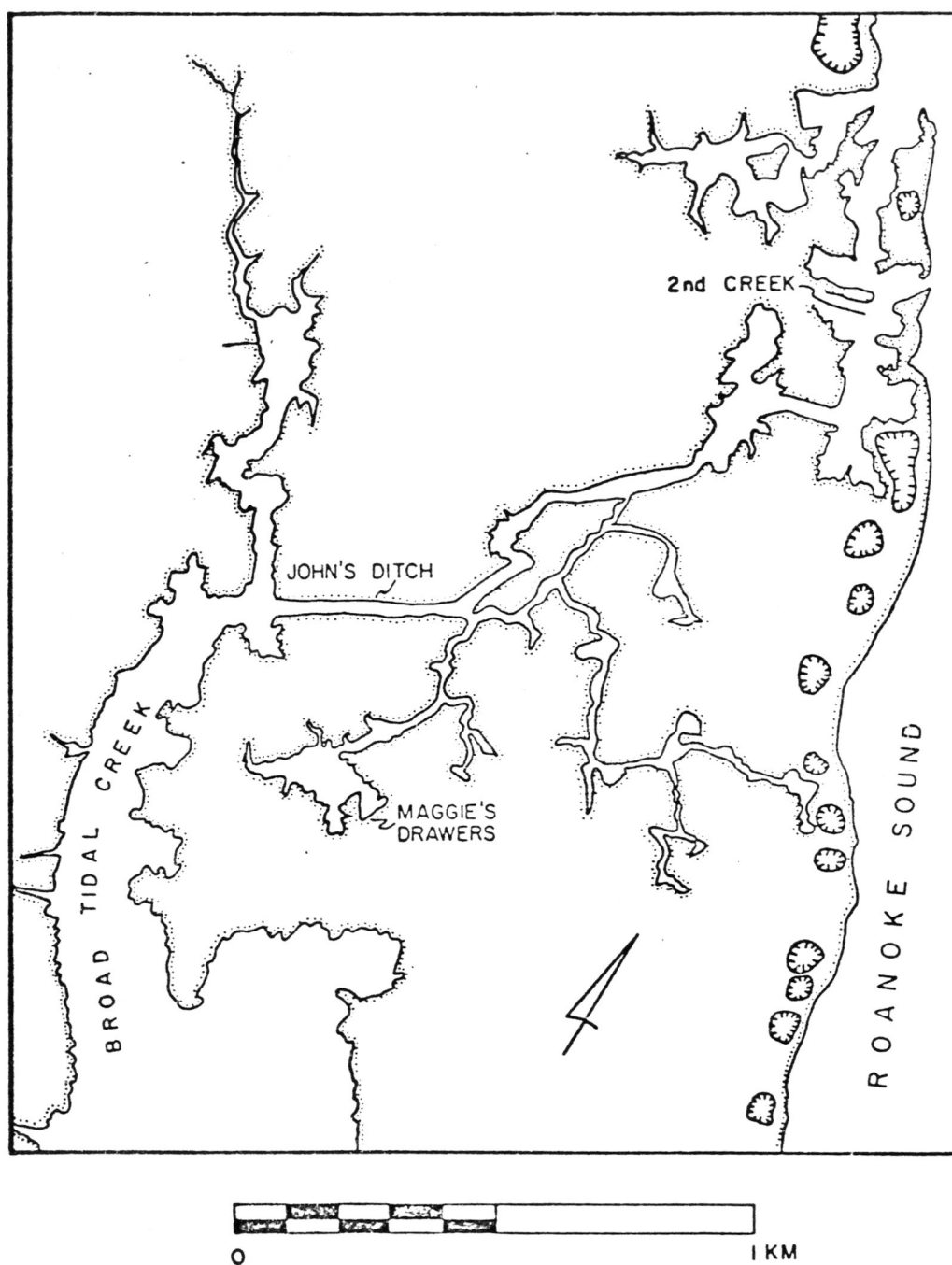


Figure 13. Tidal creek systems within the study area.

The dominant organisms within the tidal creek system include polychaete worms, an abundance of cottonmouth water moccasins (Agkistrodon piscivorus) and nonpoisonous water snakes (Natrix sp.). Some scattered Myriophyllum spicatum growing in the upper portions of the tidal creeks is the only submergent aquatic plant found in the study area.

Two major sedimentary environments, tidal creek channels and channel shoals, are found within the tidal creek system.

Tidal Creek Channels

The main channel connecting the Broad Creek system with Roanoke Sound is characterized by a slightly meandering thalweg (Figure 14) averaging 1 to 3 meters in depth. Just east of John's Ditch, however, the channel undergoes a series of sharp bends and the thalweg has been scoured to as much as 6 meters deep. The deeper portions of the channel occur just south of the meander axis indicating that the southerly flow through the creek system is dominant (Leopold, Wolman and Milner, 1964).

The tidal creeks that are not a part of the main connecting system have central channels which range from 0.6 to 1.2 meters in depth. These channels do not have a thalweg and show no signs of scouring.

Most of the bottom sediment within the tidal creek system is a highly organic rich mud. The coarse fraction in UBC 1-1, for example, is 95% plant material by volume. This organic mud is up to 4 meters thick within some of the blind channels and lakes. Fine to medium sands are found in the deeper scoured sections of the thalweg and within

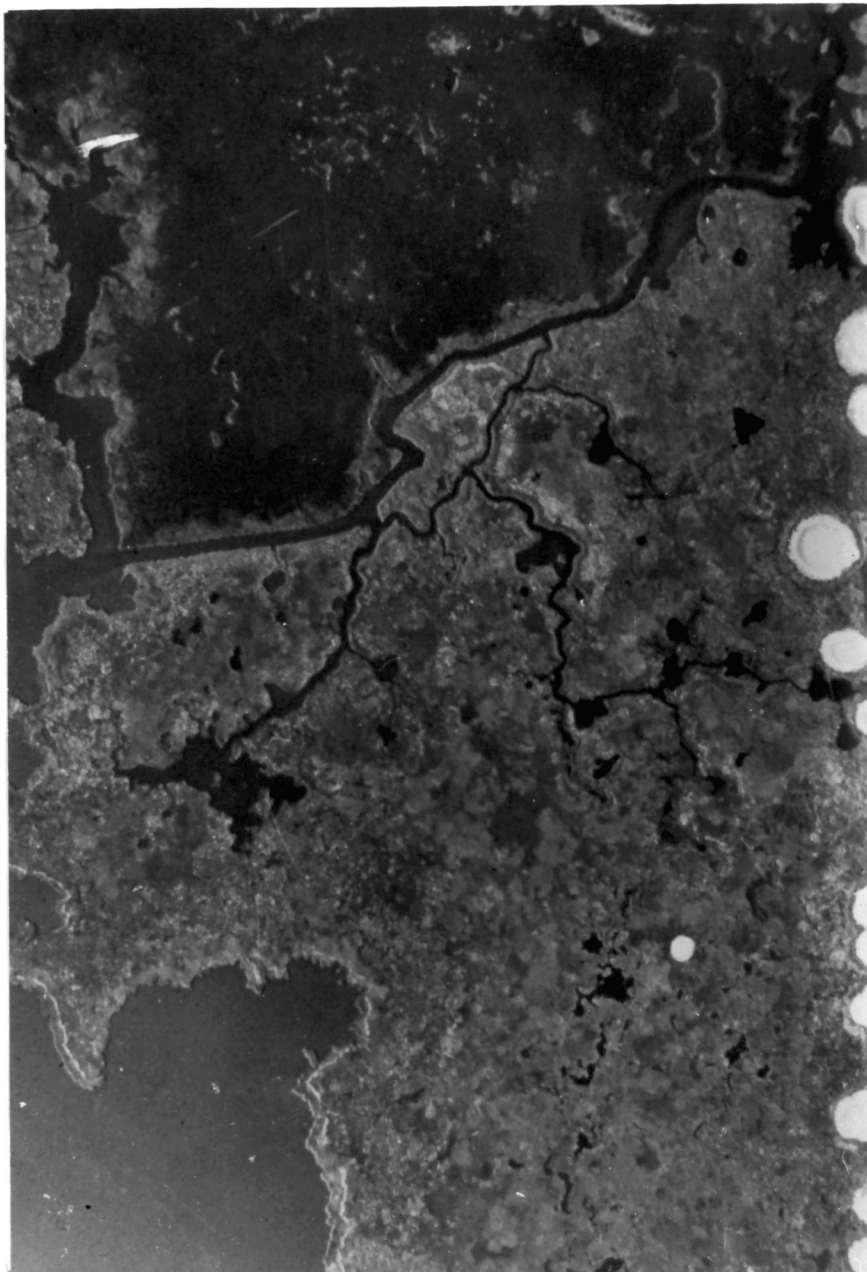


Figure 14. Tidal creek thalweg. The thalweg shows up in this photo as a dark band in the center of the main tidal creek systems, see Figure 13. (From ERTS-1 imagery dated October 25, 1965).

several of the wider portions of the blind creek system, particularly the upper portions of the original Broad Creek tidal creek. The sands are lithologically similar to those on the shelf bars (Appendix 2).

Tidal Creek Shoals

Lateral to the tidal creek channels, the highly organic rich mud commonly forms a series of shoals that build up to as high as 25 to 30 centimeters below mean water level (summer field season datum). Shoals are particularly well developed within the embayed irregularities of the shoreline flanking the main channel. Similar, but less well developed and deeper, highly organic rich mud shoals are found within the small embayment off the northeastern end of the Broad Creek embayment. Subaerial exposure of the shoals occurs only during extremely low wind tide events.

Irregularly Flooded Marsh

Marsh Physiography

The marsh system surrounding Broad Creek is a part of an extensive, irregularly flooded, brackish marsh system which covers more than one-half of Roanoke Island (Figure 15). The surface of the marsh is a horizontal plane that lies 7 to 8 centimeters above the normal water level datum established during the summer field period. The marsh shorelines are generally undercut peat scarps one-third to one meter high. Gently sloping shorelines occur only adjacent to the bay mouth bar and to a large spoil pile near the southwestern margin of Broad Creek.

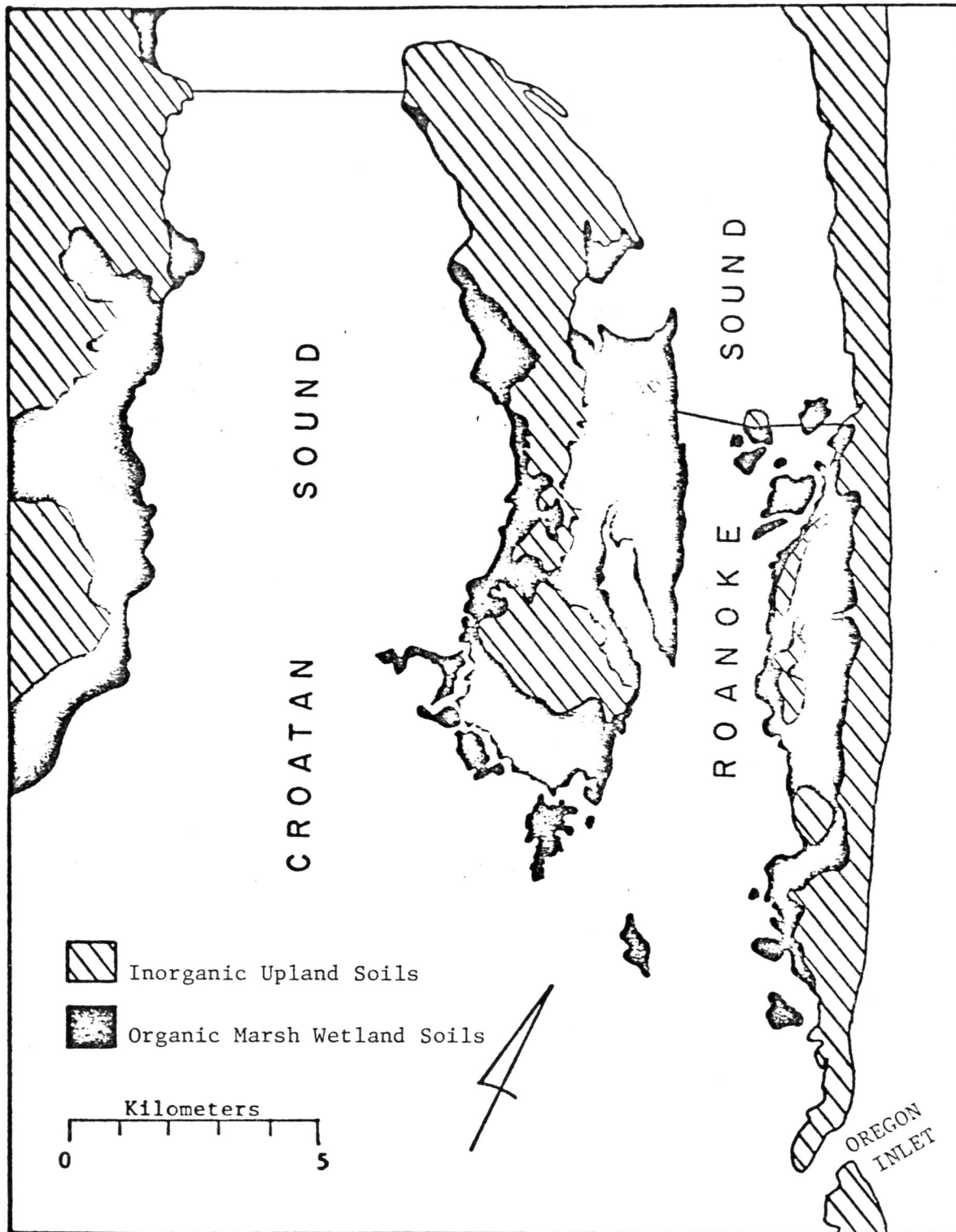


Figure 15. Relative percentages of inorganic upland soils and organic marsh wetland soils within the study area and vicinity. (From NASA U-2 infrared imagery taken January 30, 1973.)

A narrow peat bench (1 to 3 m wide) commonly extends a short distance offshore on the bay bottom. This is best developed along the eastern and southwestern shoreline of Broad Creek. Peat also forms the floor of most of the small embayments and irregularities along the shoreline of the bay. Many of these small embayments are shallow features created by the erosion of the upper 15 to 25 centimeters of marsh peats that may be a meter or more thick. Erosion is enhanced by the burrowing activity of fiddler crabs (Uca pugilator) (Figure 16) along the marsh shoreline.

The marsh surface is pocked with numerous, irregular, shallow (<1 m) ponds, many of which are interconnected by small channels. These features are especially abundant in a zone that extends down the center of the marsh peninsula separating Broad Creek from Roanoke Sound (Figure 17). Also dotting the marsh surface are a series of topographic highs or hammocks. These features are underlain by inorganic soils and are characterized by non-wetland plant communities.

Man-made features within the marsh system include a series of mosquito ditches and small marina canals, many of which are flanked on one or both sides by spoils from the excavations. Larger spoil piles are present on the marsh along the Roanoke Sound shoreline and at the extreme southwest margin of Broad Creek (Figure 18).

Vegetation Zonation

Vegetation in the study area is topographically zoned into six plant community associations (Figure 19). These include from lowest to highest:

Figure 16. Biocorrosion along the marsh shoreline. Fiddler crab burrowing here has been so extensive that the normally resistant root mat on the marsh surface has been weakened and removed by wave action.

Figure 17. Aerial view of the marsh ponds in the center of the peninsula which separates Roanoke Sound from Broad Creek. The long axis of the large pond in the foreground is approximately 120 meters. The view is northwest.



Figure 16.

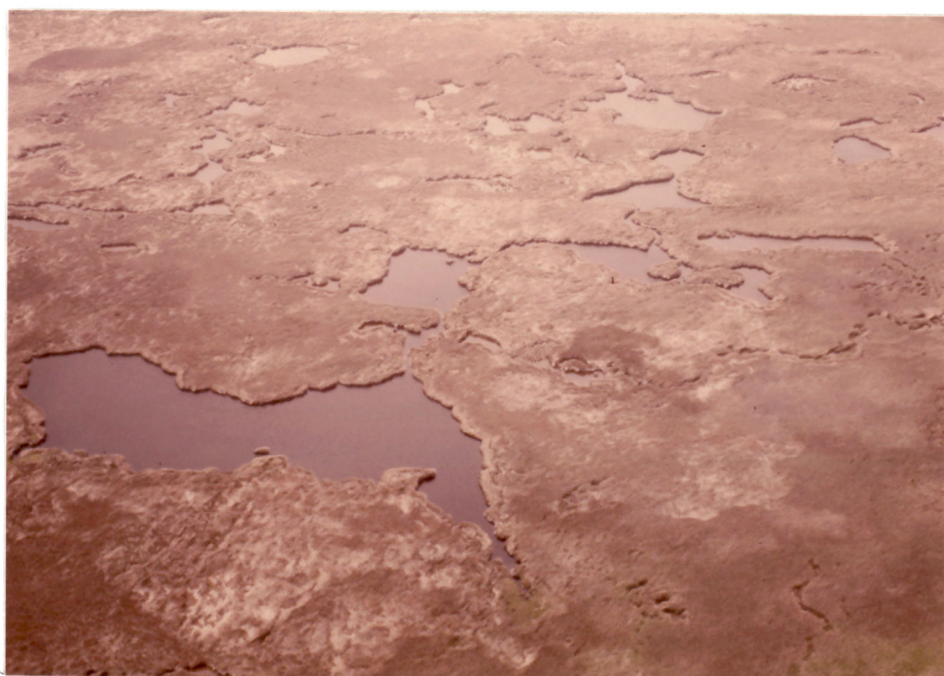


Figure 17.



Figure 18. Man-made marsh features. The barren white feature adjacent to the shoreline is a spoil disposal area resulting from the dredging of the shipping channel down Roanoke Sound. The channel which borders the highway was initially dredged to provide fill for the roadbed. It is presently serving the marina complex at the end of the road as boat dockage.

The circular patches of green in the center of the marsh (brown) are forested (dark green) or shrub populated (light green) hammocks. These are natural features and occur wherever the relief on the underlying inorganic soils intersect (forested) or nearly intersect (shrub covered) the marsh surface.



Figure 19. Vegetation distribution within the study area.

- 1) Spartina alterniflora marsh fringe,
- 2) Juncus roemerianus irregularly flooded marsh,
- 3) Iva frutescens-Spartina cynosuroides levees,
- 4) Spartina patens high marsh,
- 5) Baccharis halimifolia and Myrica cerifera shrub thickets,
- 6) pine forest community.

The Spartina alterniflora fringe occupies a narrow (1 to 5 m wide), sloping, intertidal zone along the bay shoreline. The slope is produced by the erosion of soft peat underlying the more resistant surface root zone, which then bends down. In contrast to intertidal marshes in other regions, this low marsh Spartina is a dwarfed ecotype, often looking much like a mowed lawn (Figure 20).

The next zone, only a few centimeters higher than the marsh fringe, is the broad flat Juncus roemerianus irregularly flooded marsh. This zone comprises over 95% of the marsh surface area in the study area (Figure 21). The marsh consists of dense stands of Juncus roemerianus with individual leaves 1.5 to 2.0 meters high (Figure 22).

Juncus begins to thin along the landward margins of the irregularly flooded marsh. Commonly, a more heterogeneous community of fresh marsh plants, such as Typha latifolia and Cladium jamaicense, is found (Figure 23). Since the elevation of the fresh marsh surface is essentially the same as that of the Juncus roemerianus marsh surface, the fresh marsh species are apparently controlled by fresh ground water seepage from the adjacent mineral soils.

Iva frutescens and Spartina cynosuroides levees make up the next zone. Best developed along the more exposed shorelines of Broad Creek,

Figure 20. Spartina alterniflora marsh fringe. As can be seen in this photo, the Spartina alterniflora fringe is not universally present and Juncus roemerianus may grow right to the edge of the shoreline.

Figure 21. Juncus roemerianus irregularly flooded marsh. The Roanoke Sound bridge and the old Roanoke Inlet flood tide delta can be seen on the horizon. View looking east.



Figure 20.



. Figure 21.



Figure 22. Black needlerush
(Juncus roemerianus).

Roanoke Sound and to a lesser extent along the tidal creek system, these narrow (2 to 10 m wide), low (less than 1 m high), levees occur between the Spartina alterniflora fringe and the irregularly flooded Juncus marsh. Spartina cynosuroides, a tall (2 to 5 m high), robust grass generally found in lower salinity systems dominates the levees surrounding most of the embayment. Smaller, more discontinuous levees along the tidal creek system and more protected portions of Broad Creek are colonized by Iva frutescens (Figure 24).

At the southwestern tip of Broad Creek peninsula, the area exposed to the greatest fetch of southwesterly winds that produce high wind tides, is a small Spartina patens high marsh (Figure 25). This was the only representative of what might be considered classic tidal marsh zonation within the study area. The elevation of this system is similar to the elevation of the levees which it grades into further up Broad Creek.

The shrub thicket and pine forest community zones are found associated with mineral soils along the mainland side of the marsh and on hammocks within the marsh. Baccharis halimifolia and Myrica cerifera dominate the shrub zone which occupies the narrow juncture between mineral and organic soils (Figure 26). Just landward, above the influence of all except extreme wind tides, is the pine forest community (Figure 27). Pine forests are found on many of the higher elevation hammocks, but several have only the shrub zone. A few that are nearly buried by the marsh exhibit only a thinning of Juncus roemerianus with some admixture of other herbaceous species.

Spoil piles within the study area are relatively barren. A narrow shrub zone around their bases grades upward into a thin xeric

Figure 23. Fresh marsh zone. Normally the fresh marsh zone which occurs adjacent to the inorganic uplands is the same elevation as the rest of the marsh and is colonized by Caladium jamaicense or typha sp. in the study area. In this photo Eleocharis sp. is colonizing a small shallow fresh pond.

Figure 24. Tidal creek levees. The light green boarder along the tidal creek is a relatively indistinct levee colonized by Iva frutescens.



Figure 23.



Figure 24.

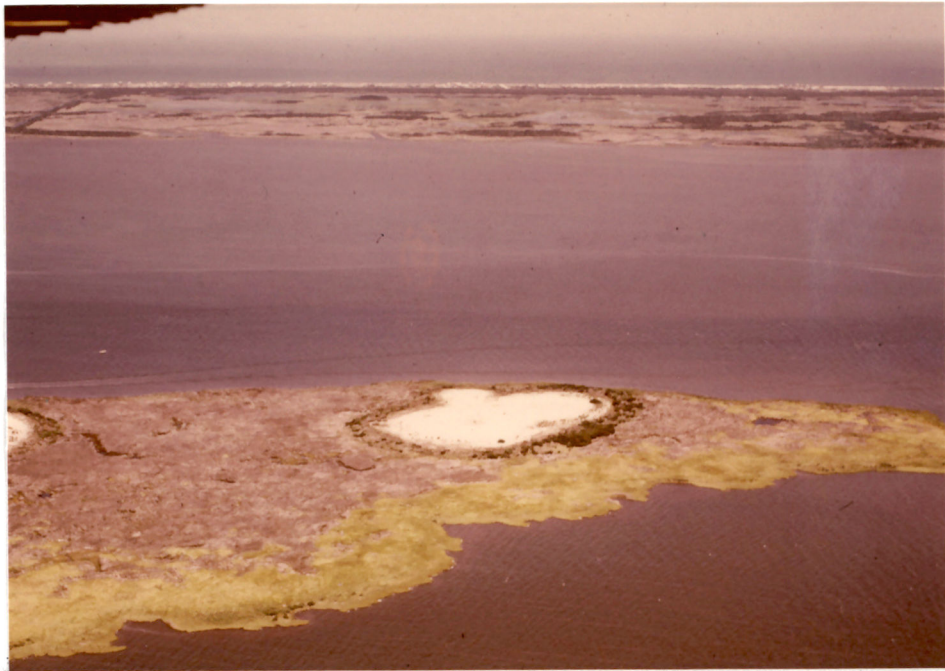


Figure 25. Spartina patens marsh. The relatively broad (for the study area) strip of light green is Spartina patens growing on a broad low levee. This portion of the study area has the greatest exposure to wave energy during southwesternly winds and high wind tides. The darker green ribbons within the Spartina patens which appear toward the left side of the photograph, upstream, are Spartina cynosuroides and shrub patches. Spartina cynosuroides dominates the levee further upstream where it is not as wide and where the shoreline has greater protection from wave action.

Figure 26. Shrub zone. The junction between the organic marsh and inorganic upland soils is colonized by a shrub zone dominated by Myrica cerifera and Baccharis halimifolia. Notice the marsh is dominated by Caladium jamaicense here.

Figure 27. Upland pine forest. The complete sequence of the inland edge of the marsh vegetation zonation pattern from Juncus roemerianus to upland pine forest can be seen in this aerial view.



Figure 26.



Figure 27.

community of Andropogon sp., Panicum sp. and other grasses and herbs.

Marsh Peat

The results of laboratory sample analyses are summarized in Table 7. The lithology of the marsh peat is more variable than the other units described. The percentage of fine grained material ($>4 \phi$) ranges from 23% to 95% by weight. Organic material makes up from 35% to nearly 100% of the coarse fraction.

The distinctive vegetative zonation pattern was not obviously reflected by laboratory analysis of the marsh peat. The techniques used were not adequate to differentiate the relatively subtle differences which probably exist. However, the percentage of fine grained ($>4 \phi$) material did decrease with distance from the shoreline levees (Figure 28).

A typical sample from the modern marsh (Table 7) consists of a dark brown, muddy (80% $>4 \phi$ by weight), slightly sandy peat. The organic material (95% of the coarse fraction by volume) is dominantly fine fragments of vascular and epidermal plant tissue. The upper 20 centimeters generally contains root material which can be recognized as belonging to the plant species growing on the marsh surface directly above. Fine to medium grained quartz sand dominates the inorganic coarse fraction and the samples rarely contain any grains coarser than coarse sand. Sorting tends to be slightly better (medium well to well sorted) than the other units within the study area, and like the central basin muds, mica is the dominant accessory mineral. Unlike any other

TABLE 7. IRREGULARLY FLOODED BRACKISH MARSH SAMPLE SUMMARY

NO. SAMPLES: 14	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂
FINE FRACTION ($>4\phi$)						
Weight %	60%-95%	80%	11.0	14%	81-90%	50% 61-70% 21%
COARSE FRACTION ($<4\phi$)						
Dominant Grain Size	V.Fine-Med.	U.Fine	1.6	63%	Fine	46%
Maximum Grain Size	Med.-Pebble	Coarse	1.2	19%	Coarse	46% Med. 27%
Sorting	M.Poor-V.Well	M.Well	1.4	27%		
% Fe Stained	0-25%	3%	7.4	287%		
Volume % Plant Material	85-100%	95%	5.9	6%	91-100%	79%
Fine Grassy Fragments	95-100%	99%	1.3	1%		
Dark Aggregates	0-15%	1%	3.9	282%		
Wood	One Sample Had Trace %					
Seeds	One Sample Had Trace %					
Dominant Non-Quartz Mineral	Mica (86%), Fe Agg. (14% of Spls.)					
Secondary Non-Quartz Minerals	Mica (100%), Fe Agg. (79%), Glauconite (14%), Opaque Heavies (43% of spls.)					
Fragile Shell Hash	0-1%	0.3%	0.8	256%		
Robust Shell Hash	0%					
Foraminifera	Eight Samples Had Planispirally Coiled Forms					

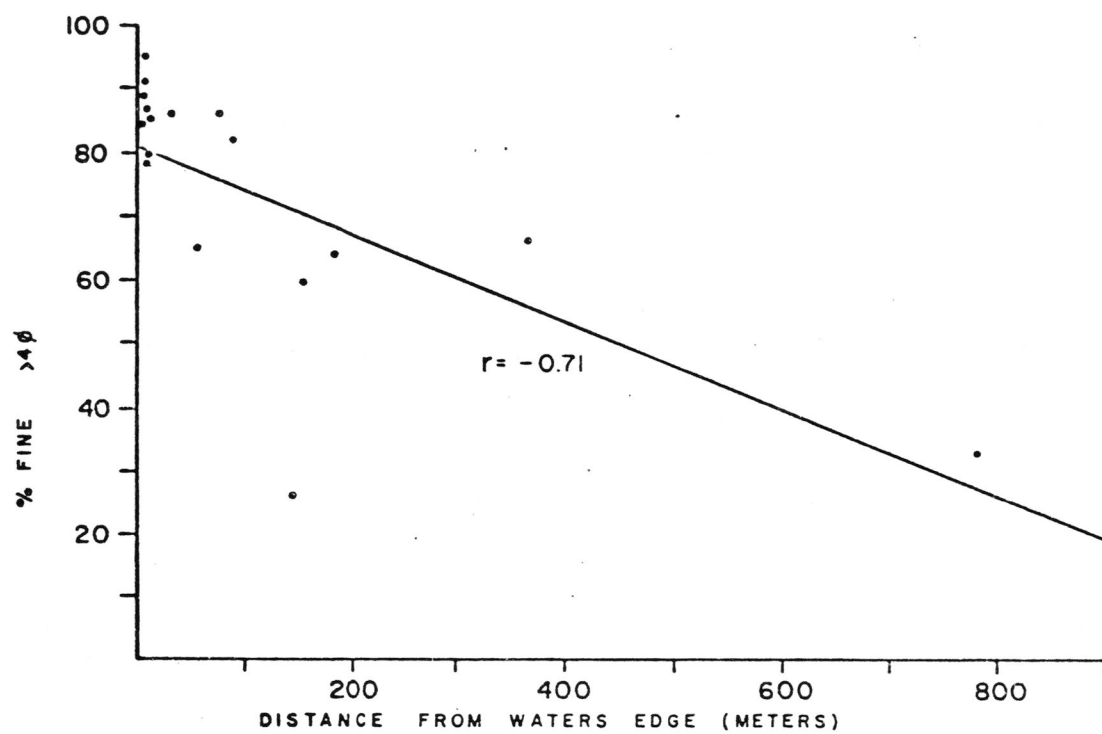


Figure 28. Weight percentage of silt and clay versus distance from the edge of the embayment in surface marsh peat samples.

unit, most (80%) of the samples contain sand sized iron aggregates, and in two samples they were the dominant accessory mineral. Planispirally coiled foraminifera were occasionally found in the peat samples. The bay shelf was the only other unit in which these forams were observed.

In addition to the brown muddy peat, two other fine grassy fragmental peat types can be differentiated on the basis of the percent coarse organic and percent fine fractions: 1) a clean peat and 2) a sandy muddy peat. The clean peat, present in only two samples, has a fine fraction ranging from 23 to 33% by weight. All the other parameters are essentially the same as the muddy peat. One of the samples, C68-1 was collected 600 meters from the nearest water body and followed the general trend of reduced fines with distance from the shoreline. The other sample, S7-1, was collected from the erosional peat bench. This peat is not modern and it too may have been isolated from any water body at the time of its formation.

The sandy muddy peat is present in one sample, C78-1, collected from a levee along a relatively high energy section of the study area bordering Roanoke Sound. It differs from the more typical muddy peat only in the higher percentage of sand relative to the organic content in the coarse fraction.

An additional peat type was present in two samples from the erosional peat bench, S16-1 and C18-1, (Appendix 3) along the southwestern shoreline of the Broad Creek embayment. These samples consisted of clean peat with a coarse organic fraction characterized by a large percentage of dark brown to black, amorphous aggregates of highly degraded and unrecognizable material. This peat type is not

associated with any of the brackish marsh plant communities present today within the study area. The dark aggregate peat is, however, significant within the stratigraphic section and will be discussed more fully in the next chapter.

S T U D Y A R E A S T R A T I G R A P H Y

Stratigraphic Units

Examination of 77 cores 1.0 to 6.0 meters in length revealed four inorganic and three organic units (Table 8) within the study area. The stratigraphic relationships and areal extent of the various units are summarized in Figure 29. Units 4 through 7 are the product of modern processes operating within the sedimentary environments already described. Units 1 and 2 are relict throughout most of the study area. However, within the pine hammocks and along the upland marsh transition, they are forming today. Unit 3, a dark aggregate peat, is not associated with any modern environment within the study area. Therefore, it was necessary to sample other peat producing environments within the region to provide insight into the probable depositional environment of this unit.

Unit 1

Unit 1 is the basal unit upon which all of the other units within the study area have been deposited. The unit is a brown to reddish brown, clean, poorly or moderately well sorted, iron stained, fine quartz sand (Table 9 and 10). The only areal trend is an increase in the dominant grain size along the Roanoke Sound shoreline. The unit is typically thin bedded (1 to 10 cm) and occasionally exhibits gravelly erosion surfaces, both at the top and within the unit. Erosion surfaces were apparently localized and could not be traced laterally more than a few decameters.

TABLE 8. STRATIGRAPHIC UNITS

	ORGANIC	INORGANIC
MODERN	Unit 5. Highly Organic Rich Mud Environment - Tidal creek shoals	Unit 7. Clean Sand Environment - Shelf bars & bay mouth bar.
	Unit 4. Brown Fibrous Peat Environment - Brackish irregularly flooded marsh	Unit 6. Organic Rich Muds Environment - Central basin
RELICT	Unit 3. Dark Aggregate Peat Environment - Fresh marsh	Unit 2. Muddy Sand Environment - Upland- wetland transi- tion
		Unit 1. Iron Stained Clean Sand Environment - Relict soil

Figure 29. Typical cross sections of the stratigraphic units found within the study area. The black dots shown beneath the surface of the subaerial portions of the cross sections represent the maximum penetration of a probe. The numbered vertical lines show the location and penetration of cores. Hasch marks on the core lines represent sample intervals. Vertical exaggeration is 83 times.

Figure 29.

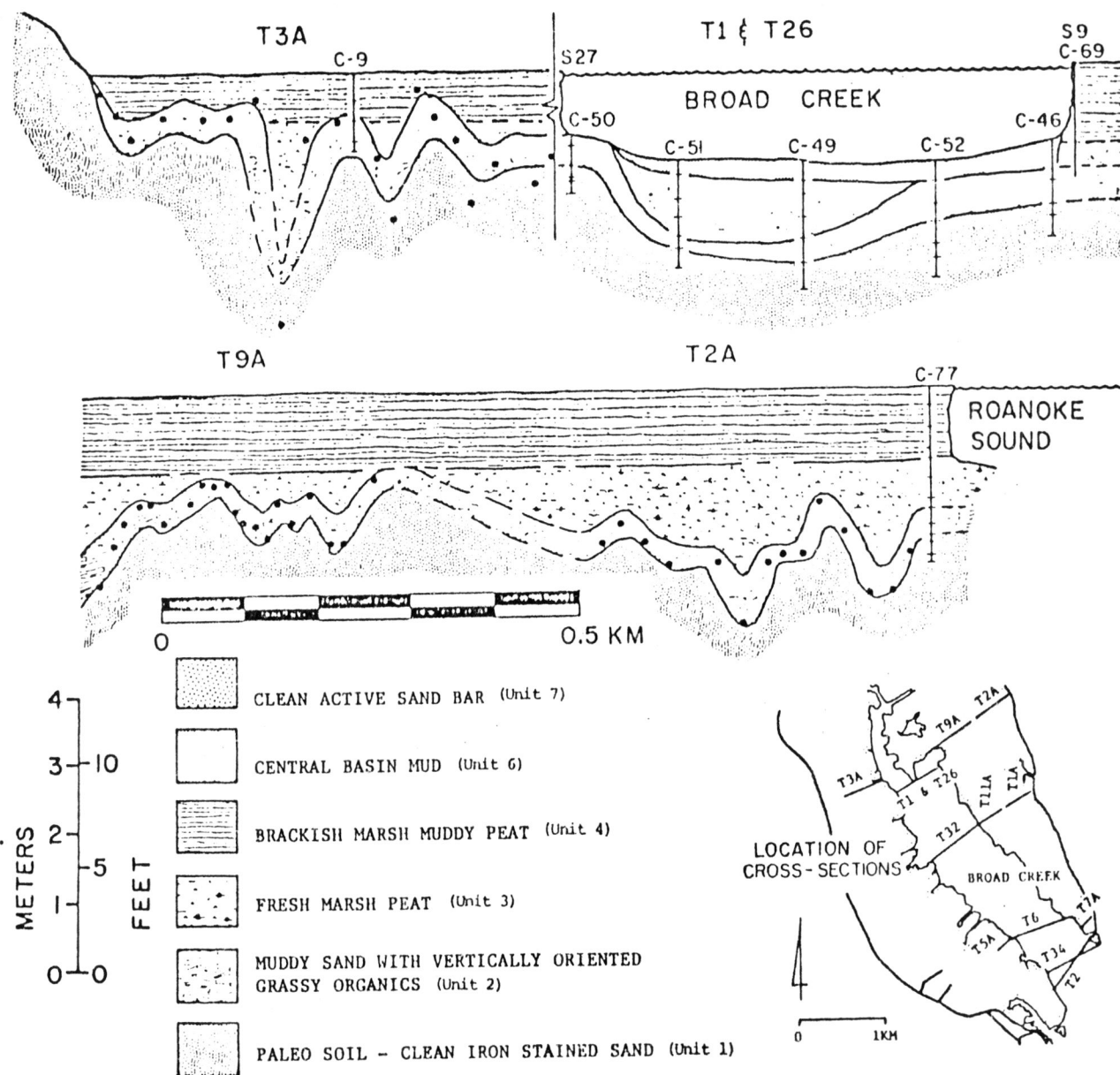


Figure 29.
(Continued)

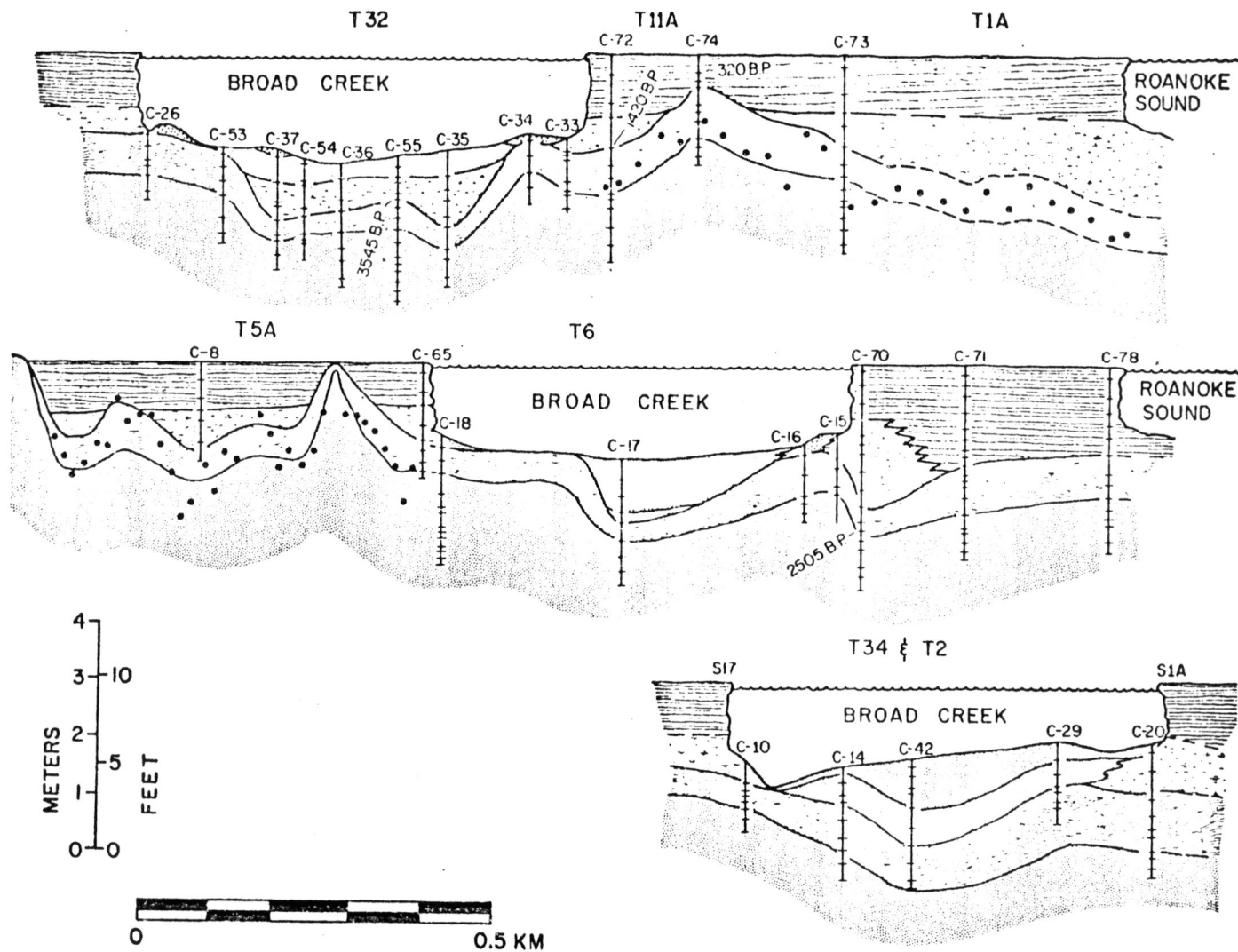


TABLE 9. UNIT 1 RELICT SOIL SAMPLE SUMMARY--UNIT SURFACE

NO. SAMPLES: 14	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂		
FINE FRACTION (>4 ϕ)								
Weight %	1%-22%	7%	5.9	80%	0-10%	79%	11-20%	14%
COARSE FRACTION (<4 ϕ)								
Dominant Grain Size	Fine-Med.	U.Fine	1.7	44%	Fine	71%	Med.	14%
Maximum Grain Size	Med.-Pebble	Gran.	1.0	14%	Gran.	57%	V.Coarse	21%
Sorting	Poor-V.Well	Mod.	1.7	47%	M.Well	36%	M.Poor	29%
% Fe Stained	1-95%	59%	40.9	69%	0-10%	29%	81-90%	29%
Volume % Plant Material	T-15%	6%	4.8	83%	0-10%	86%	11-20%	14%
Fine Grassy Fragments	0-100%	77%	31.1	40%	91-100%	50%	71-80%	14%
Dark Aggregates	0-50%	6%	13.8	222%	0-10%	79%	11-20%	14%
Wood	0-99%	17%	31.3	184%	0-10%	71%		
Seeds	0%							
Dominant Non-Quartz Mineral	Opaque Heavy Minerals (100% of spls.)							
Secondary Non-Quartz Minerals	Mica (21%), Glauconite (14% of Spls.)							
Fragile Shell Hash	0%							
Robust Shell Hash	0%							
Foraminifera	0%							

TABLE 10. UNIT 1 RELICT SOIL SUMMARY--UNIT SUBSURFACE

NO. SAMPLES: 13	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂
FINE FRACTION (>4 ϕ)						
Weight %	1%-17%	6%	5.2	90%	0-10%	77%
COARSE FRACTION (<4 ϕ)						
Dominant Grain Size	Fine-Med.	U.Fine	1.1	40%	Fine	62%
Maximum Grain Size	V.Coarse-Peb.	V.Coarse	0.8	10%	V.Coarse	48%
Sorting	V.Poor-Well	M.Poor	2.0	62%	V.Poor	31%
% Fe Stained	2%-100%	71%	40.9	57%	91-100%	54%
Volume % Plant Material	0%-15%	5%	5.6	116%	0-10%	77%
Fine Grassy Fragments	0%-100%	65%	40.9	63%	91-100%	38%
Dark Aggregates	0%-90%	9%	24.7	288%	0-10%	92%
Wood	0%-100%	18%	31.7	177%	0-10%	69%
Seeds	One Sample Had Trace					51-60% 15%
Dominant Non-Quartz Mineral	Opaque Heavy Minerals (100% of spls.)					
Secondary Non-Quartz Minerals	Mica (23%), Glauconite (15% of spls.)					
Fragile Shell Hash	0%					
Robust Shell Hash	0%					
Foraminifera	0%					

Organic material makes up relatively low percentages of the unit's coarse fraction. Fine fragments of vascular and epidermal tissue are the dominant organic component. The unit is unique in its high wood content relative to the other units within the study area. However, the organic content generally decreases with depth in the unit.

Elevations on the surface Unit 1 within the study area range from 1.0 meter above mean sea level to 3.0 meters below mean sea level. The surface of the unit is a gently rolling plain which probing indicates has been dissected by a relict drainage system. The relict drainage system consists of a trunk stream or channel approximating the center of the present Broad Creek embayment. This channel is deepest at the mouth of the bay suggesting a southerly drainage pattern. The open water embayment has occupied only the trunk stream during the present marine transgression while the smaller laterals have subsequently filled with peat.

The iron staining, relief and relict drainage on the surface of Unit 1 indicates that it is a relict soil that represents the hiatus separating the upper or Holocene units from the middle and lower units reported by O'Connor and Riggs (1974). Though no fossils were found in Unit 1 within the study area, the general lack of silt and clay and the bedded nature of the unit suggest that it represents the high energy barrier island or shoal facies of O'Connor and Riggs' middle unit.

Since Unit 1 is laterally continuous with the modern soil of the forested upland and hammocks of the study area, it is a relict soil only where it has been transgressed by marsh and estuarine deposits. Comparison with samples from the modern upland soil suggests that the

soil surface undergoes some diagenesis during the transgression. The majority of the modern soil samples have a much higher percentage of organic material, particularly wood, than does the relict soil. Much of the wood in the relict soil and transgressive unit samples appear charred. This charring could be the product of carbonization or a more rapid diagenetic process, fire. Fire has been and still is a common occurrence in the marshes and forests within the region. It could account for a reduction in the total organic and wood percentages found in the relict soil samples. A rising water table and more regular flooding would retard regeneration of forests in burned areas being transgressed.

Unit 2

Unit 2, a light gray to tan, plastic, muddy sand 0.3 to 1.0 meter thick, overlies the Unit 1 relict soil everywhere throughout the study area except: a) on the forested uplands, b) in the scoured portions of the tidal creek channel, and c) where the relict soil is exposed on the bottom of the Broad Creek embayment. The muddy sand unit has partially filled in the topography on the relict soil resulting in a more subdued relief on the top of Unit 2.

One of the distinguishing characteristics of this unit is the presence of vertical, in place grass stems having an average density of one to two leaves per square centimeter. Though the plastic nature of the Unit 2 sediment made it difficult to trace the total length of an individual leaf, some do extend through one-third of the thickness of the unit. Species identification of the grasses was not possible in most cases. Some of the samples, however, contain recognizable Juncus

roemerianus while others contained grasses that were positively not Juncus.

Unit 2 is a light gray to tan, muddy ($>4 \phi = 24\%$ by weight), moderately to moderately well sorted coarse fraction, fine grained sand. The dominant non-quartz constituents, which make up only 1% to 2% of the coarse fraction, are opaque heavy minerals. Comparison of the top, middle, and bottom sections of the unit (Tables 11, 12, and 13) revealed few significant differences. There is an upward fining trend and a slight upward increase in organic content. Although fine grassy fragments dominated the organic fraction throughout the unit, the percentage of dark amorphous aggregates increased toward the top. Areally, the unit tended to be coarser grained and more poorly sorted toward Roanoke Sound.

Two possibilities for the origin of Unit 2 were considered: 1) that it is a component of the relict soil (Unit 1); or 2) that it is a separate post-soil unit. Because Unit 2 generally follows the contour of Unit 1 and because these two relict units contrast markedly with the overlying units that have documentable modern examples, it was tempting to interpret Unit 2 as a component of the relict soil. However, closer examination of the evidence indicates that Unit 2 is post-soil in origin. Soil profiles on the relict barrier islands in the region, such as Kitty Hawk Woods system, typically have a humus surface layer underlain by clean iron stained sand. No clay accumulation zones occur. Relict estuarine deposits which have undergone pedogenesis may exhibit a clay accumulation zone, but it occurs below the humus and upper portions of any iron staining which may be present. Within the study area the

TABLE 11. UNIT 2 MUDDY SAND SAMPLE SUMMARY--UNIT SURFACE

NO. SAMPLES: 16	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂		
FINE FRACTION (>4φ)								
Weight %	11%-32%	24%	6.1	25%	21-30%	75%		
COARSE FRACTION (<4φ)								
Dominant Grain Size	Fine-Med.	U.Fine	1.2	39%	Fine	44%	U.Fine	25%
Maximum Grain Size	Coa.-Pebble	Grain.	0.9	12%	V.Coarse	50%	Gran.	25%
Sorting	V.Poor-Well	Mod.	1.9	50%	Mod.	25%	V.Poor	25%
% Fe Stained	0-25%	3%	6.0	186%	0-10%	94%		
Volume % Plant Material	2-20%	10%	5.8	56%	0-10%	68%	11-20%	31%
Fine Grassy Fragments	0-100%	57%	41.2	73%	91-100%	31%	0-10%	25%
Dark Aggregates	T-90%	34%	35.9	106%	0-10%	50%		
Wood	0-40%	7%	11.6	171%	0-10%	81%		
Seeds	Two Samples Had Trace %							
Dominant Non-Quartz Mineral	Opaque Heavy Minerals (100% of spls.)							
Secondary Non-Quartz Minerals	Mica (13%), Fe Agg. (6% of spls.)							
Fragile Shell Hash	One Sample Had Trace %							
Robust Shell Hash	0%							
Foraminifera	0%							

TABLE 12. UNIT 2 MUDDY SAND SAMPLE SUMMARY--UNIT MIDDLE

NO. SAMPLES: 15	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂
FINE FRACTION ($>4\phi$)						
Weight %	7%-32%	21%	7.8	38%	21-30%	53%
COARSE FRACTION ($<4\phi$)						
Dominant Grain Size	Fine-Med.	U.Fine	1.3	47%	Fine	73% Med. 20%
Maximum Grain Size	Coa.-Pebble	V.Coarse	0.8	11%	V.Coarse	60% Coarse 20%
Sorting	M.Poor-Well	Mod.	1.0	24%	Mod.	47% M.Well 27%
% Fe Stained	T-10%	3%	3.5	102%		
Volume % Plant Material	2-25%	10%	6.9	73%	0-10%	67% 11-20% 27%
Fine Grassy Fragments	70-100%	92%	10.1	11%	91-100%	67% 81-90% 20%
Dark Aggregates	0-30%	5%	7.8	157%	0-10%	93%
Wood	0-20%	3%	5.2	178%	0-10%	93%
Seeds	0%					
Dominant Non-Quartz Mineral	Opaque Heavy Minerals (100% of spls.)					
Secondary Non-Quartz Minerals	Mica (7%), Fe Agg. (7% of spls.)					
Fragile Shell Hash	0%					
Robust Shell Hash	0%					
Foraminifera	0%					

TABLE 13. UNIT 2 MUDDY SAND SAMPLE SUMMARY--UNIT BASE

NO. SAMPLES: 7	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂
FINE FRACTION (>4 ϕ)						
Weight %	8%-26%	16%	9.2	56%	11-20%	43%
COARSE FRACTION (<4 ϕ)						
Dominant Grain Size	Fine-Med.	U.Fine	1.2	43%	Fine	57%
Maximum Grain Size	Coa.-Gran.	V.Coarse	0.7	10%	V. Coarse	57%
Sorting	V.Poor-Well	Mod.	1.8	43%	Well	29%
% Fe Stained	T-20%	4%	7.2	190%	0-10%	86%
Volume % Plant Material	T-18%	7%	6.3	92%	0-10%	86%
Fine Grassy Fragments	70-99%	93%	10.7	11%	91-100%	71%
Dark Aggregates	0-30%	6%	11.0	173%	0-10%	86%
Wood	0-2%	0.5%	0.7	141%		
Seeds	0%					
Dominant Non-Quartz Minerals	Opaque Heavy Minerals (100% of spls.)					
Secondary Non-Quartz Minerals	None					
Fragile Shell Hash	0%					
Robust Shell Hash	0%					
Foraminifera	0%					

muddy sands of Unit 2 overlies the iron stained sands of Unit 1.

Similarly, several cores from the deeper portions of the paleodrainage system have a thin, organic rich layer at the top of Unit 1. The organic fraction on this surface includes leafy material and bark, which gives it the general appearance of a humus horizon. Again, overlying this surface is Unit 2. Probably the most convincing evidence that Unit 2 is post-soil in origin is that it is confined to those portions of the study area which have been transgressed by the marsh and estuarine units. It was not found beneath the hammocks or upland modern soil surface.

Within the aquatic environments of the study area, Unit 2 may be:

1) buried by central basin muds; 2) buried under a thin layer of shelf bar sand; 3) exposed on and forming the erosional or bypass surface of the bay shelf; or 4) scoured or eroded away exposing Unit 1. Unit 2 could be the product of mixing shelf bar or bay mouth bar sand and central basin mud, a process which is occurring along the boundary between the central basin and bay shelf. This mode of formation does not explain the broad areal extent of Unit 2 or the characteristic growth position of vertical organics, some of which were identified as Juncus roemerianus, a non-submergent aquatic plant.

The areal extent of Unit 2, its range in elevation, its absence above present sea level within the study area, and the grassy vegetation within the unit all indicate that it is a supratidal basal transgressional unit which forms along the upland soil-marshy wetland boundary. This boundary zone is characterized by transitional plant communities which marshward from the shrub zone include a mixture of fresh and brackish marsh species. Typically, neither community is developed to its full

potential. Apparently organic production is relatively low so the transgressional unit forms without the major input of organic material which dominates the formation of marsh peat.

Unit 3

Overlying Unit 2 throughout most of the study area is Unit 3, a dark brown to black, amorphous organic unit. This unit grades from a sandy transitional basal layer to a relatively pure peat ranging from 0.3 to 2.0 meters in thickness ($\bar{x}$ = 0.8 meters). Within the Broad Creek embayment this unit is confined to the deeper portions of the central channel and to fringing areas along the bay shore. The surface of Unit 3 where it is present within the embayment is usually a gravelly, burrowed erosional surface. The greatest areal continuity and thicknesses of this unit occurs beneath the marsh system surrounding Broad Creek. Here the top of the unit grades into Unit 4, a lighter brown, more fibrous peat without any evidence of an erosional or non-depositional surface. The elevation of the top of Unit 3 is consistently 1 to 1.4 meters below the marsh surface, except in the extreme southeastern portion of the study area where it drops. Within C-78, Unit 3 is missing and the brown fibrous peat of Unit 4 directly overlies Unit 2 at 1.7 meters below the marsh surface.

The dark, amorphous aggregate peat of Unit 3 (Table 14) is typically relatively clean (fine fraction = 31% by weight). Dark aggregates average nearly 80% of the coarse organic fraction. Fine grassy fragments, derived at least in part from the dark aggregates, make up most of the rest. Quartz sand makes up a relatively low ($\bar{x}$ = 8% by volume) percentage

TABLE 14. UNIT 3 DARK AGGREGATE PEAT SAMPLE SUMMARY

NO. SAMPLES: 18	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂
FINE FRACTION (>4 ϕ)						
Weight %	4%-74%	39%	19.7	50%	21-30%	33% 41-50% 22%
COARSE FRACTION (<4 ϕ)						
Dominant Grain Size	Fine-Med.	U.Fine	1.4	45%	Fine	53% Med. 33%
Maximum Grain Size	Fine-Gran.	Coarse	1.9	31%	Coarse	27% V.Coarse 27%
Sorting	V.Poor-V.Well	Mod.	2.0	46%	M.Well	27%
% Fe Stained	T-2%	0.4%	0.6	151%		
Volume % Plant Material	20-100%	83%	27.6	33%	91-100%	56% 71-80% 22%
Fine Grassy Fragments	T-70%	23%	25.5	110%	0-10%	56%
Dark Aggregates	29-98%	71%	28.4	40%	81-90%	28% 91-100% 22%
Wood	T-40%	4%	9.3	228%	0-10%	94%
Seeds	T-1%					
Dominant Non-Quartz Minerals	Mica (28%), Opaque Heavy Minerals (28% of spls.)					
Secondary Non-Quartz Minerals	One Sample Had Mica					
Fragile Shell Hash	0%-T					
Robust Shell Hash	0%					
Foraminifera	One Sample Had Milioline Forms					

of the coarse fraction. Dominant grain size values range from fine to medium. Sediments range from very poor to very well sorted. Opaque heavy minerals are the dominant accessory mineral in approximately one-half of the samples; mica is dominant in the rest. Mica, however, is usually absent in samples where opaque heavy minerals dominate.

The transitional basal layer of Unit 3 (Table 15) is either similar to or gradational between the units directly above and below. Generally, the percentage of mica, coarse organic material, and dark aggregates increases upward within the basal layer.

Unit 3 type peat is not obviously associated with any of the modern depositional environments of the study area. Therefore, a series of samples was collected from three other major marsh types within the region for comparative purposes. These included: 1) a regularly flooded Spartina alterniflora salt marsh on the floodtide delta shoals at Oregon Inlet; 2) a high energy, irregularly flooded, brackish marsh exposed to high windtides during northeasters at the south end of Pamlico Sound; and 3) irregularly flooded, fresh marsh systems off the Pamlico River (Figure 30).

The regularly flooded salt marsh system developing on the Oregon Inlet shoals is underlain by a thin sandy peat overlying clean medium grained shoal sands. No muddy sand (Unit 2) typical of the transition from inorganic to organic units was found. Peat samples (Appendix 4) consist of moderately to moderately poorly sorted, medium grained sandy peat to peaty sand. The organic material consists of fine grassy fragments, many of which are still recognizable fragments of Spartina alterniflora rhizomes and rootlets.

TABLE 15. UNIT 2 - UNIT 3 TRANSITION SAMPLE SUMMARY

NO. SAMPLES: 7	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂
FINE FRACTION ($>4\phi$)						
Weight %	17%-48%	32%	9.4	30%	31-40%	57%
COARSE FRACTION ($<4\phi$)						
Dominant Grain Size	Fine-Med.	L. Med.	1.4	35%	Med.	42%
Maximum Grain Size	Coa.-Gran.	V. Coarse	0.8	12%	V. Coarse	42%
Sorting	V. Poor-M. Well	Mod.	1.5	36%	M. Well	57%
% Fe Stained	T-3%	1%	0.8	58%	0-10%	100%
Volume % Plant Material	30-60%	44%	13.4	30%	31-40%	42%
Fine Grassy Fragments	0-99%	49%	38.6	79%		
Dark Aggregates	T-95%	45%	38.8	86%	0-10%	29%
Wood	0-15%	6%	5.3	88%	0-10%	86%
Seeds	One Sample Had Trace %					91-100% 29%
Dominant Non-Quartz Minerals	Opaque Heavy Minerals (86% of spls.)					
Secondary Non-Quartz Minerals	Mica (29% of spls.)					
Fragile Shell Hash	0%					
Robust Shell Hash	0%					
Foraminifera	One Sample Had Milioline Forms					

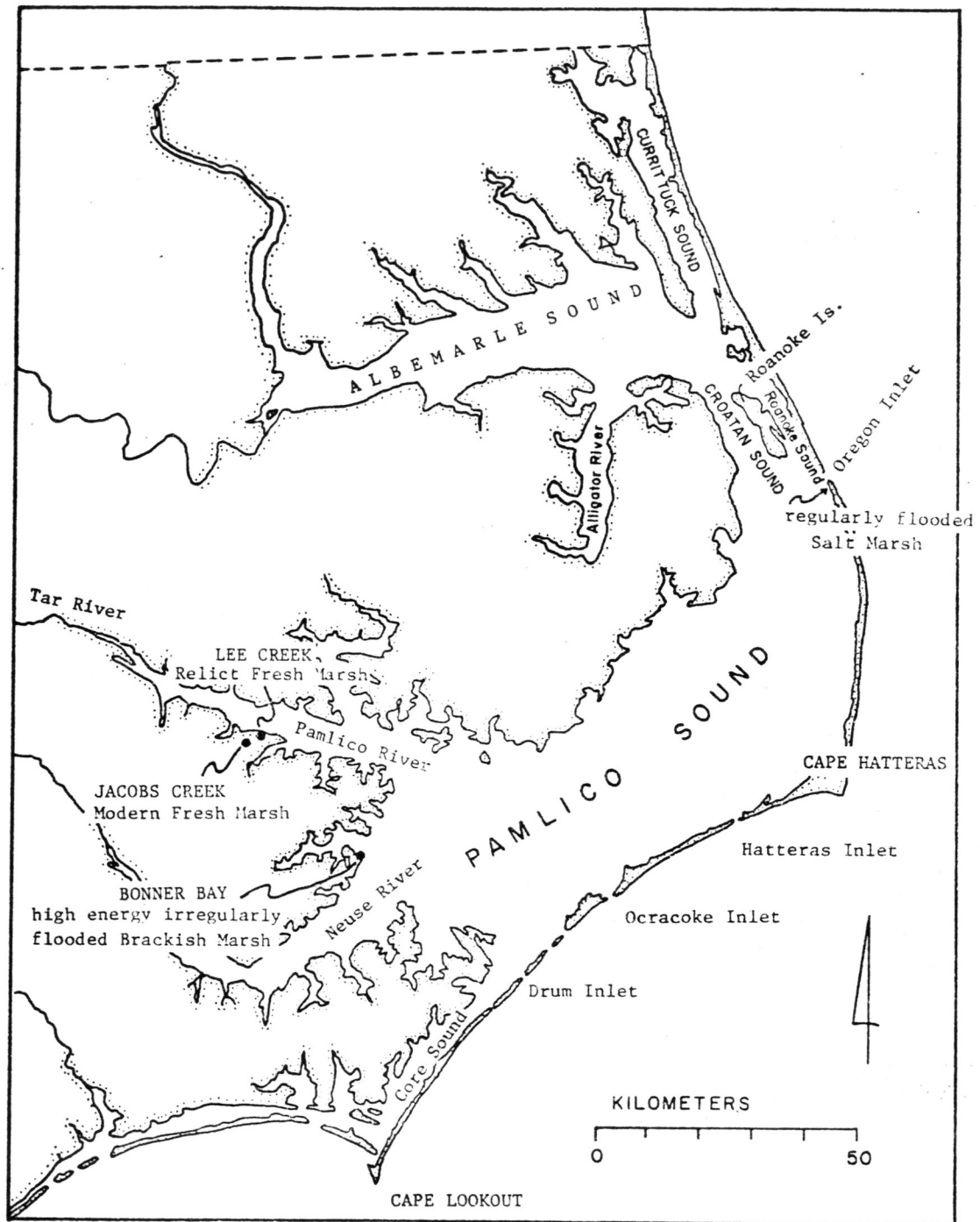


Figure 30. Locations of auxiliary marsh sampling stations.

The dark aggregate peat of Unit 3 is clearly not a regularly flooded Spartina alterniflora peat. In fact, the clean sand to sandy peat sequence of the Oregon Inlet shoals is not found anywhere within the study area. None of the Broad Creek organic systems have formed in a manner similar to the Oregon Inlet marshes.

The high energy, irregularly flooded brackish marsh system at the southern end of Pamlico Sound has a Spartina alterniflora shoreline fringe backed by a broad, flat Juncus roemerianus system, a vegetation pattern similar to that found in Broad Creek. Natural levees behind the Spartina alterniflora fringe are larger and sandier than those found within the study area, however. Vegetation on the levees includes Borrichia frutescens, Iva frutescens and Spartina patens. The marsh is underlain by approximately 1.0 meter of muddy, brown fibrous peat (BB-2 and 3, Appendix 4) which is being actively eroded and undercut causing the Spartina alterniflora fringe to sag downward. This sagging fringe moves with the waves and absorbs much of their energy. The sagging marsh mats are occasionally broken off to form funnel shaped erosional embayments which concentrate the wave energy producing splash fountains as successive waves hit the shoreline with a loud smack.

Just offshore, in one meter of water, the bottom consists of a thin veneer of sand on a burrowed gray, muddy sand surface. This unit (Sample BB-1, Appendix 4) is similar in appearance and lithology to the muddy sand unit in Broad Creek, and apparently it forms a similar erosional muddy sand apron.

The peat being produced by the high energy, irregularly flooded marsh is not the dark aggregate peat of Unit 3. Instead, the peat is similar to the muddy sandy peat being produced along the relatively high energy Roanoke Sound shorelines of the study area. Similarities in morphology and stratigraphy between the high energy southern Pamlico Sound system and the Broad Creek system suggest that both systems are undergoing a similar evolutionary history.

The organic accumulation beneath the fresh marsh systems at Jacobs Creek and Lee Creek off the Pamlico River, consist of a dark aggregate peat almost identical to that of Unit 3 within the Broad Creek system (Appendix 4). These fresh marsh peats, which range up to a meter or more thick are moderately well sorted, very fine to medium grained, slightly sandy to sandy and relatively clean (fine fraction = 40% to 65% by weight). Dark, amorphous aggregates make up 80% to 85% of the coarse organic fraction. Reconnaissance of a number of Lee Creek organic units exposed along the upper pit walls at the Texasgulf phosphate mine near Aurora (Figure 31 and 32) revealed considerable variation in the peat composition. Organic units range from sandy interbedded lenses with one or more woody stump and root horizons to lenses of almost pure dark aggregate peat. Clearly, the fresh marsh systems are variable and subject to rapid temporal and areal changes.

Organic lenses exposed at Texasgulf generally have a gradational contact with the underlying inorganic units. Frequently the transitional zone consists of muddy sand with grassy or woody organic material that has a vertical orientation similar to the muddy sand of Unit 2 at Broad Creek. Lateral discontinuity of the muddy sand unit at Texasgulf

Figure 31. Cross sectional view of the Lee Creek fresh marsh organic unit exposed on the upper pit wall of the Texasgulf, Inc., phosphate mine at Aurora. The fresh marsh is the darker slumping unit flanked by lighter colored more resistant inorganic units. The white "mountain" in the background is a gypsum pile which is produced as a by-product of the phosphate fertilizer production process. The view is south from inside the pit.

Figure 32. Close-up of a fresh marsh organic unit exposed on the upper pit wall of the Texasgulf mine. The stadia rod is graduated in meters and tenths of meters.



Figure 31.



Figure 32.

suggests that the processes and conditions producing it are not uniformly distributed.

The lithologic and stratigraphic similarities between Unit 3 and the fresh marsh systems strongly support a fresh marsh origin for Unit 3. Though small pockets and fringes of fresh marsh are found along the landward margin of the modern Broad Creek marsh system, no fresh marsh unit of the magnitude of Unit 3 is being produced. Where the elevation on the surface of Units 1 and 2 is higher than the general elevation on the surface of Unit 3, the overlying peat is generally not the dark aggregate fresh marsh peat of Unit 3. The conditions conducive to fresh marsh development within the study area have apparently ceased to exist.

Unit 4

Overlying the dark peat of Unit 3 within the marsh system surrounding Broad Creek is the lighter brown, more fibrous and generally muddier peat of Unit 4. The Unit 4 peat averages 1.0 to 1.5 meters thick and is thickest in the southeastern portion of the study area, adjacent to Roanoke Sound, where it directly overlies Unit 2. Unit 4 pinches out against the topographically high portions of the Unit 1 inorganic soil that form the forested upland of Roanoke Island and the hammocks dotting the marsh surface.

Lithologically, Unit 4 (Table 16) is nearly identical to the peat developing at the surface of the modern irregularly flooded, brackish marsh system within the study area. The only differences are that modern peat has 1) a higher percentage of subsurface samples with seeds, and 2) a higher percentage of surface samples with iron oxide

TABLE 16. UNIT 4 BROWN FIBROUS PEAT SAMPLE SUMMARY

NO. SAMPLES: 8	RANGE	$\bar{X}$	Sd.	Cv.	MODE ₁	MODE ₂
FINE FRACTION ($>4\phi$)						
Weight %	0%-99%	77%	32.0	42%	91-100% 50%	71-80% 38%
COARSE FRACTION ($<4\phi$)						
Dominant Grain Size	V.Fine-Med.	Fine	1.8	75%	V.Fine	38%
Maximum Grain Size	Fine-V.Coarse	Coarse	1.7	31%	Coarse	38% V.Coarse 25%
Sorting	M.Poor-V.Well	M.Well	1.9	36%	V.Well	38% M.Poor 25%
% Fe Stained	0%-%					
Volume % Plant Material	40%-100%	75%	25.2	34%	91-100% 50%	
Fine Grassy Fragments	50-100%	92%	17.2	19%	91-100% 88%	
Dark Aggregates	0-30%	5%	10.3	2%	0-10% 88%	
Wood	0-20%	3%	6.9	235%	0-10% 88%	
Seeds	Five Samples Had Trace %					
Dominant Non-Quartz Minerals	Mica (63%), Fe Agg. (25%), Opaque Heavy Minerals (13% of spls.)					
Secondary Non-Quartz Minerals	Mica (100%), Fe Agg. (25%), Glauconite (25% of spls.)					
Fragile Shell Hash	One Sample Had 3%					
Robust Shell Hash	0%					
Foraminifera	0%					

aggregates and foraminifera. Though the significance of the seeds is not clear, the loss of iron aggregates and forams would be expected through time as burial and a rising water table cause a shift from oxidizing to more acidic reducing conditions. Because of the lithologic similarities between the Unit 4 peat and the modern marsh system peat, and because of their stratigraphic continuity, Unit 4 is interpreted to be the product of irregularly flooded brackish marsh peat accumulation.

Units 5, 6 and 7

Units 5, 6, and 7 are relatively thin modern depositional units found within the Broad Creek embayment and tidal creeks. They have already been described so this discussion is limited to a brief outline of each unit's stratigraphic significance.

Unit 5 is the highly organic rich mud shoal system which is still developing in the lower energy portions of the study area. The unit is thin (<1 m), narrow, and irregular in plan view. If preserved, the unit would be an irregular, allocthonous shoestring deposit. It would probably be difficult to distinguish from autochthonous peat deposits.

Unit 6 is the central basin mud deposit. It is filling the main channel of the drainage system which developed on the surface of the relict soil unit (Unit 1). This linear mud unit is up to 1.5 meters thick and has a surface elevation which ranges from 0.8 to 2.2 meters below present sea level.

Unit 7 consists of the clean bar sands of the shelf bars and bay mouth bar. Shelf bar sand deposits are generally less than 30

centimeters thick. They are lithologically similar to the bay shelf muddy sand (Unit 2), which they generally overlie. The major differences are the lower percentage of silts, clays, and organic material found in the Unit 7 bar sands.

The bay mouth bar sands, on the other hand, are considerably thicker and do not necessarily overlie units with a similar lithology. One core penetrated a meter of Unit 7 bay mouth bar sand before entering the underlying Unit 6 central bay muds. The bay mouth bar is generally coarser grained than sediments from other units found within the study area.

C_{14} Ages of Stratigraphic Units

Sixteen peat and wood samples from eight cores and one bivalve shell (Cyrtopleura costata) from the study area (Figure 33) were C_{14} dated to determine the ages of the units identified and to develop a sea level curve for the region.

The C_{14} dates indicate that all of the stratigraphic units overlying the relict soil surface of Unit 1 have developed during the last 6,000 years (Figure 34). Though no samples from Unit 2 and only one sample from Unit 1 were dated, both units underlie a basal Unit 3 peat with a C_{14} date of $5,315 \pm 110$ years B.P. Units 1 and 2 also immediately underlie progressively shallower Unit 3 and Unit 4 basal peats that have progressively younger C_{14} dates. Unit 1 is still forming today above the present sea level.

These time stratigraphic relationships indicate that all of the units are time transgressive. Units 1 and 2 span the entire 5,315 years

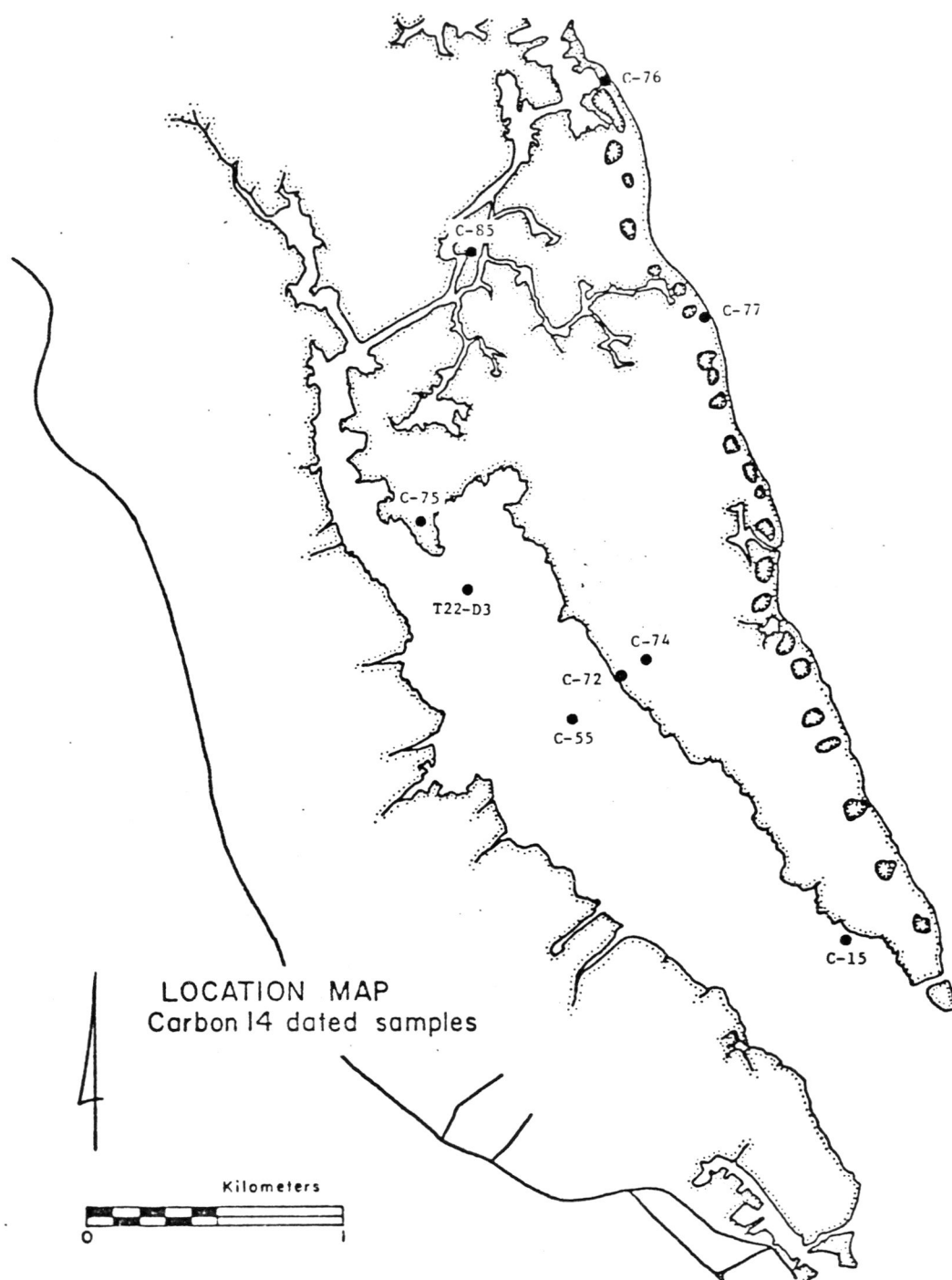


Figure 33.

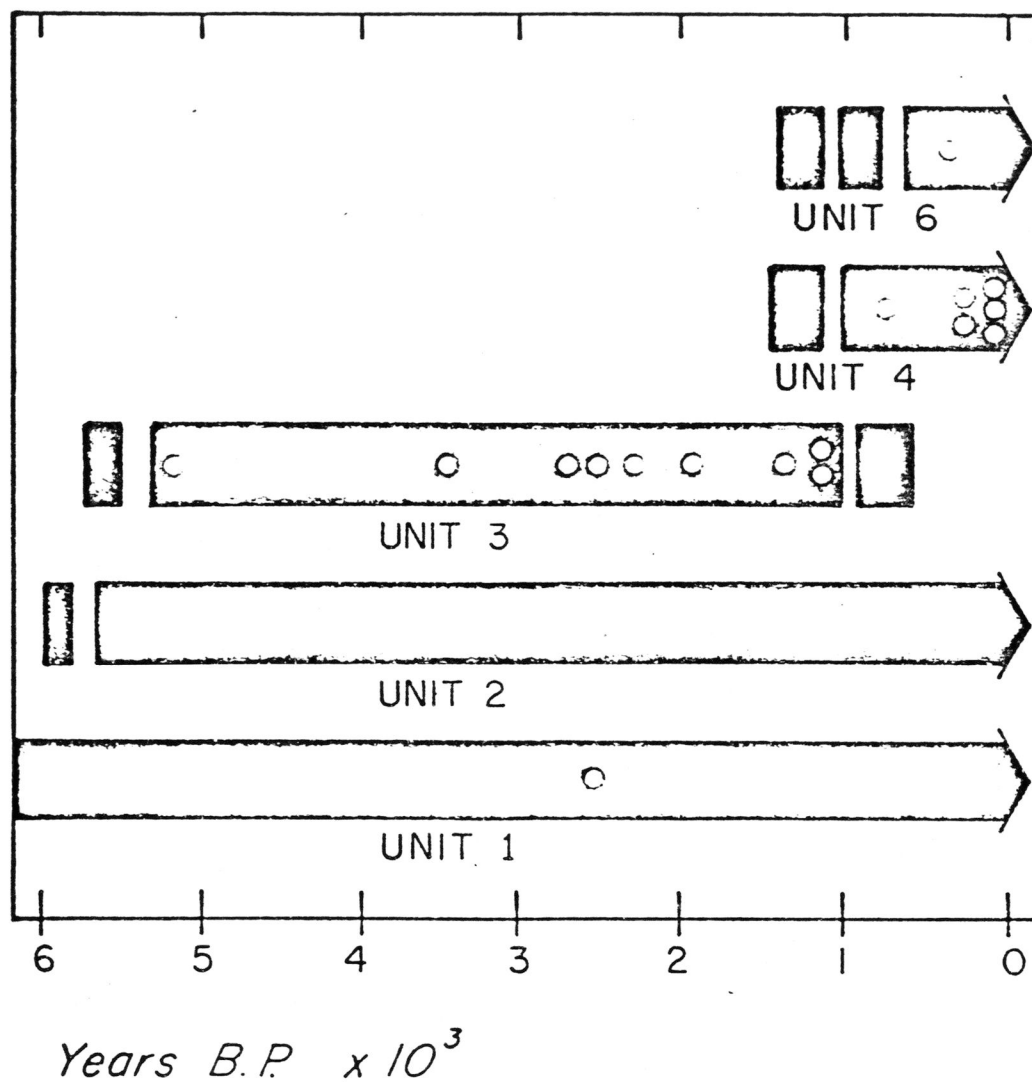


Figure 34. Time ranges of the stratigraphic units within the study area. Unit 5 is not included because of insufficient data. Sedimentation processes observed suggest that the unit probably was being deposited for as long as Unit 3, however. White dots within the time bars represent the ages of samples C_{14} dated. Arrows on the end of the time bars indicate that the unit is forming today. Breaks in the time bars represent the more speculative portions of the units range.

of the C_{14} record for the study area. Unit 3, which ranges from 5,315 years B.P. to around 1,000 years B.P., has been superseded by Unit 4, another time transgressive unit that is continuing to develop today. Within the Broad Creek embayment and tidal creek system, Unit 6 apparently began to develop at about the same time as Unit 4. Because no samples from the lower boundary of Unit 6 were dated, the onset of Unit 6 deposition is more tentative. The lack of suitable material to date makes the onset of Unit 7 deposition even more difficult to define. Stratigraphic relationships indicate that the onset of shelf bar deposition post dates the deposition of Unit 2 within Broad Creek. Similarly, deposition on the bay mouth bar post dates the onset of Unit 6 deposition. Both bar systems are still forming today. The organic material deposited within Unit 5 has been eroded from potentially considerably older organic units. Therefore, a reliable date of the onset of Unit 5 deposition is impossible.

Sea Level Changes

Nine basal peat samples ranging from 0.4 to 3.0 meters below present sea level and 4 non-basal peat samples from the thick (3 m) organic units of C-75 were utilized to develop a sea level rise curve for the study area. Basal peat samples are those collected where peats lie directly above the inorganic sediment complex; non-basal peat samples are those collected from peats that are underlain by other organic units. The data (Figure 35) show a variable but continuous rise over the past 5,000 years at an average overall rate of 5 to 10 centimeters per century. Three time periods with some-

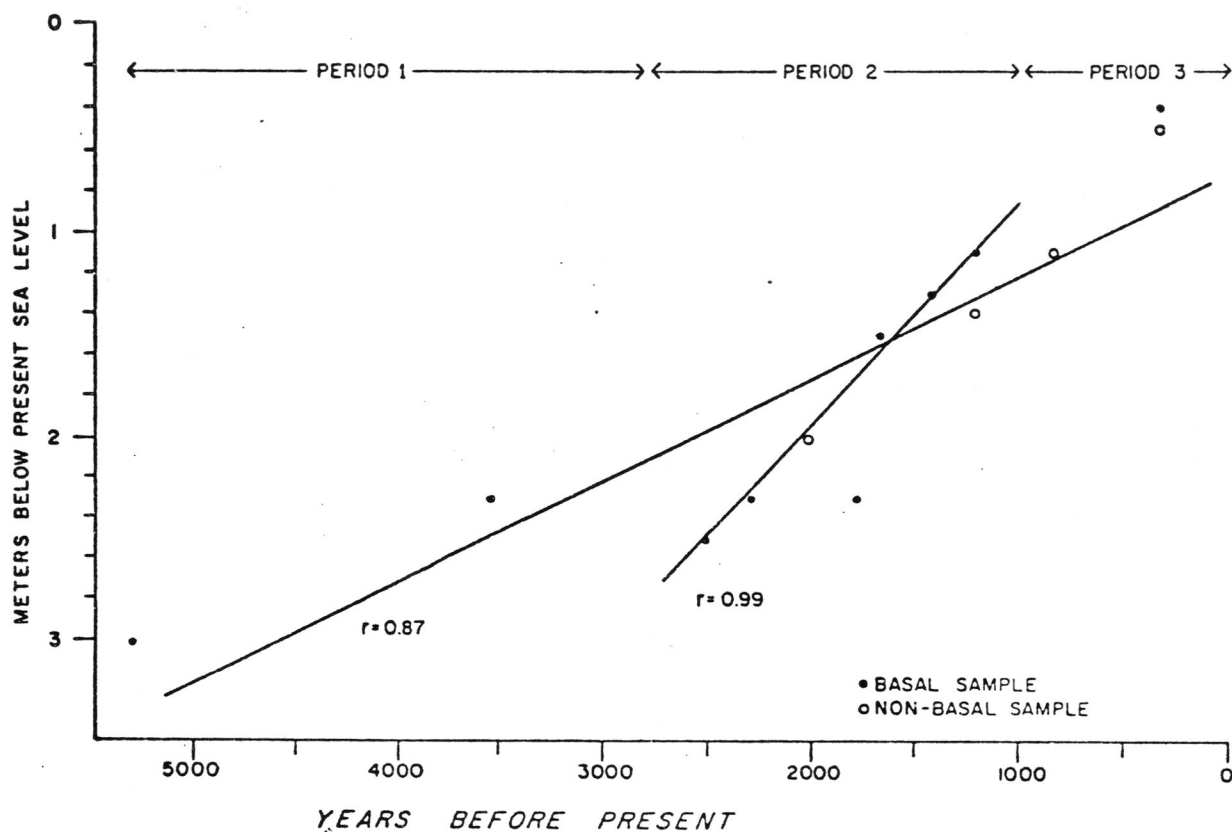


Figure 35. Sea level rise within the study area. The long curve is the linear regression for the entire time period sampled and indicates an overall rise averaging 5 centimeters per century over the past 5,000 years. The shorter curve is the linear regression for only those samples within Period 2.

what different rates of sea level rise are suggested by the curve.

Period 1 spans the 2,000 year interval between 5,000 and 3,000 years B.P. The curve indicates a 3.4 centimeters per century rate of sea level rise during this period. The sparsity of dated samples (2) from Period 1 and the potential for sample collection and preparation error make it difficult to assess the reliability of the curve. Both samples are from transitional units below the actual onset of true organic accumulation. The samples are from a fresh organic system which may have developed above sea level. Also, the samples may have contained older organic material reworked from below.

Period 2 ranges from approximately 2,500 to 1,000 years B.P. The curve indicates an 11 centimeter per century rate of sea level rise. Because this portion of the curve includes the largest number of dated samples, six basal peats and three non-basal peats, it is thought to be the most reliable.

One basal peat sample date (C76-8) from Period 2 lies more than one-half meter below the curve, suggesting the possibility of a minor regression between 1,500 and 2,000 years B.P. The peat in C76-8 generally had a layered or bedded appearance which was unusual for a Unit 3 dark aggregate peat. The surface of the underlying Unit 2 muddy sand was unusually gravelly. Rather than indicating a regression, therefore, this sample appears to represent an allocthonous relict channel fill analogous to Unit 5 tidal creek shoals. As such, it is not a reliable indicator of sea level fluctuations.

The non-basal peat sample dates from C-75 within Period 2 plotted below the linear regression curve developed from basal peat samples due to autocompaction. The amount of autocompaction indicated by the curve is surprisingly low, however, amounting to a maximum of only 15% of the total unit thickness. This is considerably less than the 50% to 75% autocompaction reported from New England marshes by Kay and Barghoorn (1964). Autocompaction in C-75 is also somewhat unique in that the maximum compaction occurred within the middle portions of the unit rather than near the base.

Period 3 ranges from 1,000 years B.P. to the present. It is separated from Period 2 largely because continuation of the rate of rise during Period 2 would result in sea level being 25 centimeters higher today than it actually is. Apparently, the rate of sea level rise slowed slightly sometime during Period 3. However, as is the case of Period 1, too few C_{14} dates are available to develop a very reliable curve. Shallow organic units are difficult to date reliably because of the potential for contamination from modern plants. Three dates from the upper portion of C-72 had to be discarded because of what appeared to be contamination of this type, even though obviously modern roots were hand picked from the samples prior to C_{14} dating.

The sea level curve developed for Broad Creek is in close agreement with the eustatic curves based on C_{14} dating from the school of researches supporting a steady rise (Shepard, 1960; Redfield, 1967b; and Milliman and Emery, 1968). Based on the tide gauge data spanning the past 130 years from the southern Baltic and French coasts and from numerous supplementary stations, Lisitin (1974) reported an average

eustatic sea level rise of 11.2 centimeters per century. Though this rate is somewhat greater than the overall curve rate for the study region, it is very similar to the more reliable Period 2 portion of the curve. Thus, the rise in sea level in the region between 5,000 and 300 years B.P. appears to be essentially eustatic.

Working with tide gauge data along the Atlantic Coast of North America, Hicks (1973) found generally higher rates of sea level rise during the past century. However, the rates varied from a low of 7 centimeters per century at Key West, Florida, to a high of 34 centimeters per century at Portsmouth, Virginia, which suggests a tectonic influence. Balazs (1974) reported a similar trend in land elevation changes which showed up in first order releveing surveys. Reported subsidence rates of as much as 50 centimeters per century in northeastern North Carolina and land rise rates of up to 65 centimeters per century in southeastern North Carolina are of particular significance. These land elevation changes correspond with structural features involving the basement in the region (Spangler, 1950; Le Grand, 1961; and Richards, 1974) which Fairbridge (1974) maintains are revived from time to time as discontinuous tectonic motions. Sea level change rates of the magnitude produced by recent tectonic motions reported for the region were not observed in the C_{14} curve from Broad Creek. Apparently the latest cycle of tectonic motion post dates the most recent C_{14} dates obtained through this study.

MODERN SEDIMENT PROCESSES

Deposition of Fine Grained Sediments

Fine grained silt and clay sedimentation processes are relatively complex. These sediments are easily carried into suspension by the slightest turbulent motion of a water body. Mead (1972) outlines two processes which assist gravity in overcoming turbulence to allow the deposition of fine grained sediment. The first consists of flocculation of individual grains into clusters brought about by dissolved organic material or inorganic salts in the water. Once clustered, the particles being heavier than individual silt or clay particles tend to settle more quickly to the bottom. Mead maintains that not much is known about the processes or significance of flocculation caused by dissolved organics in water. However, chloride concentrations as low as 2 to 3 ppt initiate flocculation under laboratory conditions. Mead does not think this process is as significant as was once thought because field studies indicate that most estuaries have a zone of high suspended sediment concentration which is apparently not influenced by salinity. He also maintains that flocculation induced deposition can be overcome by currents as low as 20 centimeters per second. The second process that induces fine sediment deposition is filtration and pelletization by organisms. A number of recent studies (Gordon, 1966; Haven, 1966; Haven and Morales, 1972) support the significance of this process. Within Broad Creek, polychaete worms are actively pelletizing the bottom muds, and they may be playing a significant role in the deposition of fine grained sediment.

Once deposited, unconsolidated silts and clays can be carried back into suspension by currents as low as 10 to 20 centimeters per second measured 15 centimeters from the bottom (Postma, 1967). However, when the fine grained sediments begin to consolidate through the reduction of pore water volume, the critical erosion velocity increases dramatically. Postma found that fine grained sediment with only a 30% loss of its initial pore water required critical erosion velocities of 100 centimeters per second. Current activity, he maintains, tends to keep fine grained sediment, including pelletized material, agitated preventing the expulsion of interstitial water. Postma believes there are two conditions under which consolidation can take place. First, if the influx of sediment is great enough, then water expulsion can begin at a critical depth within the deposit due to the weight of the overlying sediment. Secondly, consolidation can take place where hydrological conditions are such that there are relatively long periods with little current or wave activity. The central deep portions of estuaries are commonly the sites of fine sediment deposition in northeastern North Carolina (Riggs and O'Connor, 1975; Hartness, 1977; Duque, 1978; Pels, 1967; Pickett and Ingram, 1969). Shepard and Moore (1960) attribute the flat, muddy bay bottoms of the Texas coast to their being deeper than the influence of effective wave base (Approximately $\frac{1}{2}$ the wave length of waves which can be generated within a given bay).

Fine grained sediment within Broad Creek is found suspended within the water column, as a layer on the bottom of essentially the entire study area during normal energy conditions and as a component of the marsh peat surrounding the system. Stratigraphic relationships

indicate that permanent deposition, however, is confined to the bay center, marsh surface, and blind tidal creek channels.

Non-deposition within the central basin of Broad Creek would occur when wave lengths begin approaching 4 to 5 meters with wave heights ≥ 0.5 meters, or when currents near the bottom approach 20 centimeters per second. Neither of these energy thresholds are attained during normal energy conditions within Broad Creek. Therefore, deposition of fine grained sediments can be assumed to be a response to normal energy conditions within this system. However, wave and current conditions can be sufficiently strong during high energy storm events to prevent consolidation of fine grained sediment on the shallower bay shelf and the connected tidal creek channel. Conversely, under normal energy conditions the marsh surface is subaerial, and there is no fine grained sediment deposition except during high wind tides created by at least moderately high energy conditions. The presence of coarse quartz grains in the marsh peats suggests that the high wind tide conditions can be relatively high energy events.

Coarse Sediment Transport and Deposition

Unlike cohesive fine grained sediment, coarse grained sediment transport and deposition is related primarily to the velocity of the fluid transporting medium. The mechanisms of coarse grain transport include suspension, saltation, and surface creep or traction (Inman, 1949; Visher, 1969). These transport mechanisms are related to grain size in estuarine and shallow marine environments and certain grain size values represent boundaries between the different transport mechanisms.

Sediment transported in suspension is limited to material finer than 0.125 millimeters (very fine sand and smaller); sediment transported by saltation, to 0.5 to 0.128 millimeters (fine to the lower limits of coarse sand); and sediment transported by traction, to larger grains (Custer and Ingram, 1974; Allen, Castaing and Klingebiel, 1972).

The predominance of muds and fine sands within the Broad Creek system suggests that the predominant transport mechanisms are suspension and saltation though the lack of coarser material could also result from lack of a source. Minor coarse sands, granules, and even pebbles, however, do occur within most of the environments, including the marsh surface which should be a relatively low energy system. Since coarse grains rarely make up more than a small percentage of the sediments, they probably do not represent a true traction population. Rather, the concentration of coarse grained sediment appears to be generally related to erosion or non-depositional surfaces and, as such, represents lag concentrations. Stratigraphic and lithologic relations indicate that the only significant sand sized sediment being transported into the study area today is on the bay mouth bar system at the mouth of Broad Creek. Aerial photos (Figure 36) show a southerly sediment transport pattern for the region. Therefore, this sediment is apparently working south as littoral drift along the western edge of Roanoke Sound after being eroded from adjacent shorelines and the relict Roanoke Inlet flood tidal delta. The bay mouth bar is by far the largest and thickest accumulation of sand sized sediment related to present energy and hydraulic conditions. Within Broad Creek the modern sand sized sediment is derived from eroding marsh shorelines, the surface of the bay shelves and, to a

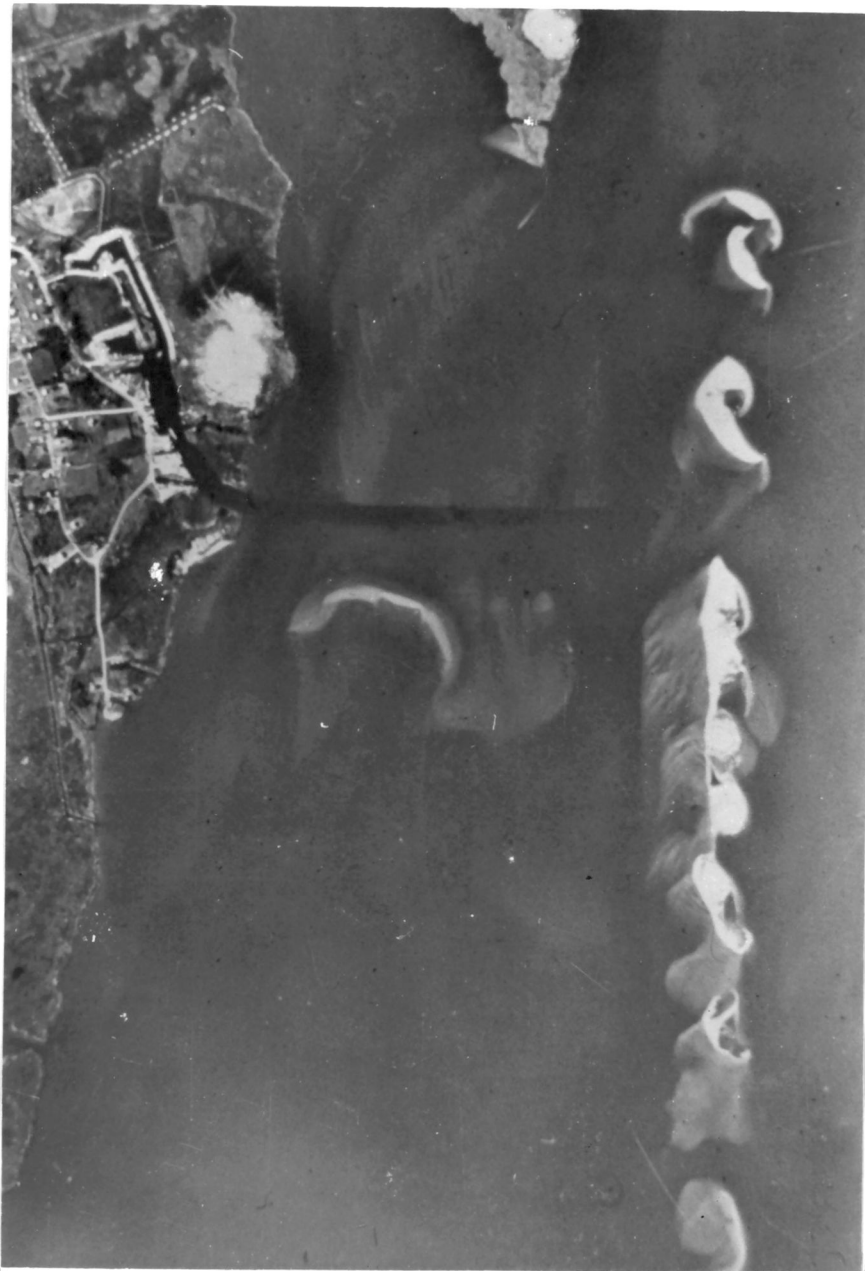


Figure 36. Regional sediment transport patterns. The sediment bars and shoals which have developed at the mouth of Broad Creek and adjacent to dredge spoil islands illustrate the predominance of the southerly transport of sand sized bottom sediment.

lesser extent, scour along meander bottoms in the connected tidal creek system. This sediment is forming the series of thin shelf bars adjacent to the shorelines and is spreading in blanket deposits over peat and mud within the small bays with a northeast exposure. Some of the sediment is being thrown up on the marsh surface during storms, particularly along the more exposed shorelines near a shelf bar source. Some of the sand sized sediment is also being transported during storms into the central basin where it is incorporated into the muds.

Intertidal Depositional System

Estuarine shoreline zones are characteristically gently sloping equilibrium features developed in response to: 1) the types and amount of sediment available; 2) the land topography; and 3) the type of energy system affecting the shoreline. Estuarine shorelines exposed to significant wave energy develop sand beach shorelines in which sediment migrates: 1) along the shoreline in response to obliquely breaking waves, and 2) offshore during high energy conditions and onshore during normal energy conditions (Komar, 1976). Wave dominated estuarine shorelines do not accumulate significant mud deposits because energy levels are high enough to prevent the consolidation and permanent deposition of fine grained sediment.

Estuarine shorelines which are protected from significant wave energy normally develop finer grained, gently sloping tidal flat shorelines. Clays, silt, and fine to medium grained sand are reported by van Straaten (1961) to move onto tidal flats through the following physical processes driven by the tides: 1) scour lag (Hjulstrom, 1935, van Straaten

and Kuenen, 1958); 2) settling lag (Postma, 1954, 1967); and 3) tidal cycle time-velocity asymmetry (Postma, 1961; Groen, 1967).

Sediment distribution patterns on tidal flats typically parallel the shoreline and occur in landward fining zones which correspond to decreasing energy conditions (Klein, 1977). Commonly tidal flats are progradational and produce a fining upward stratigraphic sequence (Klein, 1971).

Marsh systems nearly always occur on the higher elevations of tidal flats and become an important component of the sedimentary processes which produce the upward fining progradational sequence. In his classic studies of the Barnstable marshes, Redfield (1967a; 1972) found that marshes began to form after a progradational spit reduced wave energy conditions within the bay to the point that tidal driven sedimentation processes could predominate. Once the tidal flats began to develop, marsh plants began to colonize them stabilizing the sediments with their roots and dissipating energy at the sediment surface with their leaf clumps. The marshes then became an integral part of the upward fining progradational sequence.

Because of Broad Creek's small size, its protection from Roanoke Sound, and its orientation perpendicular to predominant winds, it is an environment which would be dominated by tidal energy if it were located in an area with a greater astronomical tidal range. Protected embayments as near as the Newport River off Bogue Sound, where the higher tidal range on the ocean side of the barrier islands coupled with more numerous and closely spaced inlets gives rise to a 1.0 meter tidal range, have mud flat shorelines (Figure 37). The astronomical

tidal range within Broad Creek however, is less than 1/3 meter and it does not have a tidal flat shoreline system. Instead of a gently sloping shoreline with topographically zoned depositional features (Figure 38), the Broad Creek shoreline is characterized by a step-like geometry. Here an erosional and/or non-depositional subaqueous surface intersects an erosional scarp capped by a depositional subaerial marsh system. This geometry cannot be attributed to lack of a sediment source or to the presence of unusual currents. In fact, the lack of current related bed forms indicates that currents are much more significant on tidal flat systems. Wave energy is essentially limited to internally generated wavelets because of the surrounding and enclosing marsh and bay mouth bar. Thus, the shoreline also lacks wave built beach slopes. However, waves do play a relatively significant role in the sedimentation process.

The lack of tides is probably the most significant reason for the step-like shoreline geometry since tidal flat size and the thickness of depositional units are related to tidal range. Hayes (1975) reported a gradual decrease in the significance of tidal flats relative to other coastal morphological features with a decrease in tidal range. He considered tidal flats to be unimportant when the tidal range is less than $\frac{1}{2}$ meter. Thus, there appears to be a major break in low energy shoreline sedimentation processes at this $\frac{1}{2}$ meter value. Consequently, I propose a new division within the microtidal classification of Davies (1964); coastal systems with a tidal range of $\frac{1}{2}$ meter or less should be considered significantly different and should be called "nanotidal."

Figure 37. Mud flats exposed during low tide along the Newport River off Bogue Sound near Morehead City, North Carolina.

Figure 38. Undercut erosional scarped shoreline illustrating the step shoreline geometry typical of irregularly flooded marshes within northeastern North Carolina.



Figure 37.



Figure 38.

EVOLUTIONARY PROCESSES

Origin and Evaluation of the Broad Creek System

At the onset of the study, two hypotheses on the origin of the study area were considered: 1) a gradual cut off of Broad Creek from Roanoke Sound by spit progradation, or 2) the gradual drowning of a paleodrainage system.

The first hypothesis would require that the peninsula separating Broad Creek from Roanoke Sound, most of the bay proper, and probably portions of the marsh along the western boundary of Broad Creek be underlain by an open bay basal stratigraphic unit similar to the clean sands which dominate Roanoke Sound. Instead, a paleosol forms the base of the Holocene units throughout the study area. Similarly, no trace of the spit was found by the cores or the probing traverses. All the stratigraphic, sedimentologic and unit geometry relationships within the study area point to the second hypothesis, the drowning of paleo-drainage systems. This drowning process is related to the regional large scale evolutionary development of the northeastern North Carolina estuarine system described by Riggs and O'Connor (1975) and to the Delaware Bay area as described by Kraft (1971). The general sequence found includes 1) a dissected paleosol base sequentially overlain by 2) fresh water and then 3) salt water units.

Broad Creek was an upland creek throughout the Wisconsin glacial stage, downcutting a channel through an undulating plain which averaged 2 to 3 meters below present sea level within the immediate study area. Local relief within the channel and floodplain ranged from 1 to 2 meters. Upstream, the channel and floodplain average 3.4 and 1.8 meters

below present sea level, respectively, and downstream, 4.3 and 2.4 meters below present sea level respectively. The slope of both flood-plain and channel is approximately 0.2 meters per kilometer.

The original creek system from which Broad Creek has evolved was not large. Paleochannels beneath the marsh are typically only 15 to 30 meters wide. Even the main channel beneath the Broad Creek embayment was difficult to locate because it is narrow.

Rate of Environmental Change

From C_{14} dates, the rate of sea level rise and the topographic relationships of the units within the study area, a relatively detailed scenario can be developed for the rate of environmental change. Two interpretations are given for the older events. One of these utilizes the compound sea level curve, 3.4 centimeters per century for the period earlier than 3,000 B.P., and 11 centimeters per century for later periods. The other figure represents an average whole-curve rise of 10 centimeters per century. This provides a maximum and a minimum age which reflects the limits of accuracy of both the curve and the determination of the onset of the event described. Ages for events from Periods 2 and 3 on the curve are determined on the basis of an average rise for both periods at 10 centimeters per century. Elevations on organic units are adjusted by using the 15% compaction measured within the study area.

The upland creek system began to experience the effects of the transgressing sea sometime between 4,500 and 7,300 years B.P. The impact of this transgression began in the southern portion of the study area, and possibly also in the north. The drowning influence was confined to

the floodplain until approximately 2,500 years B.P. when the floodplain in the southern portion of the study area was overtopped, followed by a rapid lateral expansion of the fresh marsh system over a broad, flat interstream area. By 1,800 B.P., this process had occurred along the entire main creek system. Approximately 1,500 years B.P., the fresh marsh system began to shift towards a brackish marsh dominated by Juncus roemerianus along the southeast edge of the study area. This process was slow and initially confined to the southeast, but later spread rapidly across the fresh marsh system. By approximately 1,000 B.P., the marsh system throughout the entire study area had become brackish. Since that time, the brackish marsh environment has dominated the study area, producing nearly a meter of vertical organic peat accumulation.

This same stratigraphic sequence can be seen areally along many of the upstream tributaries to the Pamlico and Neuse River systems. Juncus (brackish) marshes dominate the drowned floodplains near the tributary-estuarine confluence. Upstream, the channel gradually narrows and a shift in marsh plant composition to Spartina cynosuroides or Cladium and/or Typha occurs. Still farther upstream, a shrub zone (Myrica and Baccharis) gains dominance and finally, as the channel bottom and land elevation rises above the influence of the estuary, a Taxodium - Nyssa swamp forest community is found. Evidence of the continued drowning of upland ecosystems by the migrating wetland ecosystems can be seen in the form of "ghost trees." (Figure 39 and 40) These are trees which have been killed by the hydraulic stress created by drowning, and which are commonly found in the wet-dry transition zone.

Figure 39. "Ghost tree" killed by the gradual drowning of upland areas in response to rising sea level.

Figure 40. Within northeastern North Carolina ghost trees are the preferable nest building sites of ospreys.



Figure 39.



Figure 40.

Establishing the time of the onset of the major deposition of terrigenous sediments within the Broad Creek embayment is somewhat speculative with the data available. The central basin muds may have begun to accumulate immediately with the onset of transgression. However, fresh marsh peat is commonly found underlying the muds within the paleochannel, so it appears that mud deposition began somewhat later. Similarly, most of the peat older than 1,000 years B.P. within the study area is relatively clean. This suggests that the study area was isolated from any significant suspended sediment sources until that time.

The deepest mud within the Broad Creek central basin is found at the southern end of the bay at 3.5 meters below sea level. Most permanent deposition of mud at the present time is occurring at 1.8 meters below sea level. If the mud at -3.5 meters was also originally deposited at 1.8 meters below sea level, and assuming a 10 centimeters per century sea level rise, the age of the deepest mud is 1,700 years B.P. This date is very similar to the onset of the deposition of muddy brackish marsh peat at the southeastern edge of the study area.

A C_{14} date of 455 years B.P. from a specimen of Cyrtopleura costata collected in its death position from the Broad Creek central basin indicates that mud deposition began at least that long ago. Stanley (1970) describes Cyrtopleura as a deep burrower (>20 cm). The angel wing was collected from a depth of 60 centimeters below the mud sediment surface, 14 centimeters into the underlying fresh marsh peat. If the clam was 20 centimeters below the sediment surface at the time it died, then the mud was at least 6 centimeters deep at that time. It appears

that approximately 40 centimeters of mud has been deposited since the death of the clam, an average of just over 11 centimeters per century. This rate is similar to the measured sea level rise for the region, and thus provides support for the hypothesis that a critical water depth is required before permanent deposition of mud within the central basin can occur.

Expansion of the Broad Creek Embayment

The Broad Creek embayment has expanded to its present width from a narrow creek over a period of 4 to 7 thousand years. If this lateral expansion has occurred at a constant rate, it amounts to 0.10 to 0.17 meters per year (based on an average width of 670 m). If one assumes a continuous expansion, then at some point in time, as the embayment became larger, the potential for shoreline erosion from wave energy increased significantly. At that time, Broad Creek should have begun to expand more rapidly. However, analysis of shoreline changes between 1945 and 1975 showed no measureable erosion of the embayment during that period. The only change observed during that period was the localized erosion of promontaries and the enlargement of small embayments. This lack of shoreline change is difficult to reconcile when all of the marsh shoreline within the study area is undercut and dominated by erosional scarps. Perhaps these erosion scarps are a function of a very recent increase in the rate of sea level rise, which may be in part tectonic (Hicks and Crosby, 1974; and Balazs, 1974).

Another possible explanation may be that the marsh is "flowing" toward the edges and eroding at approximately the same rate. Marsh

peat has nearly no shear strength (Pestrong, 1969). Redfield (1972) reported a "slumping process" along the Barnstable marsh creek channels where the peat is thick. He found cracks forming which extended several feet and opened to a width of a foot or more between the slump margin and the undistributed marsh surface. As the blocks break off, they are decomposed and the detritus is carried away. The location of tidal creek channels appeared to be relatively stable and controlled by relict drainage channels which formed at an earlier time. In spite of the tortuous pattern of the channels, he found only two places where meanders had been cut off to form oxbow lakes. It would be difficult to maintain a stable channel with slumping shorelines if the material slumped were not replaced. Cracks similar to those observed by Redfield in the Barnstable marshes have been observed along the marsh shoreline margins within Broad Creek (Figure 41). In some cases, the weak spots appear to be related to or augmented by crab or muskrat *nutria* burrows.

A driving mechanism for this "flow" could be the surplus of organic matter necessary to maintain the marsh surface elevation at 6 to 8 centimeters above sea level, compensating for the organic material lost to oxidation, compaction, etc. This surplus productivity would have to be dealt with in some manner where surface flushing is as inefficient as it must be on the broad expanses of irregularly flooded marshes. Stiven and Plotecia (1976) estimate only 10% of the annual production on North Carolina's irregularly flooded marshes are flushed off. By contrast, Teal (1962) estimates as much as 45% of the annual organic production is flushed off the regularly flooded marshes of



Figure 41. Cracks in the marsh surface root zone caused by the more rapid erosion of less resistant underlying peat.

Georgia. Another source of surplus productivity could be the annual production of roots and rhizomes below the ground. De la Cruz and Hackney (1977) found subsurface productivity nearly equal to that above ground for Juncus roemerianus in Mississippi. Similar relationships have been reported for Spartina alterniflora in North Carolina (Stroud, 1976) and considerably higher subsurface productivity has been reported in Massachusetts (Valiela, Teal and Persson, 1976). All this productivity introduces organic matter into an anaerobic system where breakdown is considerably slower than in oxygenated systems.

Because of its low density, the marsh peat probably is in "floating" equilibrium with normal water level conditions. It seems that the periods of greatest stress on this equilibrium, periods when "flow" would most likely occur, would be during 1) exceptionally low wind tides, 2) ponding caused by heavy rainfall, or 3) a rapidly dropping high wind tide where water would be trapped temporarily behind the natural levees along the marsh shorelines.

Mainland Type Marshes Versus Barrier Island Type Marshes

The model presented for the origin of the broad, flat, irregularly flooded marsh around Broad Creek is a regional process. The origin can be summarized as a gradual drowning of low fresh water wetland systems in response to a rising sea level accompanied by the vertical growth and accumulation of marsh peat, on which the salinity influence gradually increases upward. These marshes are more closely tied to the relict topography of the mainland than to any physical coastal process and are, therefore, termed mainland type marshes.

The mainland marshes have a distinctly different origin and evolution than the marshes found on the backside of the barrier islands (Godfrey and Godfrey, 1974). On the basis of extensive core data, areal distribution patterns, and historical documentation, the Godfreys found that back barrier type marshes were dependent on the physical processes of inlet flood tidal delta formation and overwash to develop a suitable marsh plant pioneering habitat. Both environments are characterized by a large influx of new sediment. Also, inlet areas in northeastern North Carolina are characterized by the greatest astronomical tidal range and highest salinities. Both environments and their controlling physical processes are confined to the barrier island.

The Godfreys found that new overwash fans and inlet delta shoals were quickly colonized by pioneering Spartina alterniflora (Figure 42). Once established, these marshes begin building a sandy peat layer through organic accumulation and sediment trapping (Figure 43). Initially, vertical accretion typically is greater than sea level rise so these marshes quickly evolve into "high marshes." At that time, they reduce their rate of vertical accretion since they are flooded less frequently by the tides. The Godfreys found that the peat was rarely very thick beneath the back barrier type marshes which led them to conclude that marsh formation processes are very dynamic. This, they felt, was advantageous in that it continuously provides new habitat for the low marsh development which interacts with the estuaries so efficiently. Since intertidal or "low marshes" have a greater potential nutrient and organic detrital exchange with the estuarine system, they are generally considered to be more critical to estuarine productivity.

Figure 42. Spartina alterniflora pioneering
new shoals of the Oregon Inlet flood tidal delta.

Figure 43. Well established Spartina
alterniflora marsh on the Oregon Inlet flood
tidal delta shoals.



Figure 42.



Figure 43.

In general, the back barrier type marshes, particularly where they form on inlet shoals, are more closely related to developing tidal flat type marshes, such as those described by Redfield (1972). Overwash fans have a different origin than tidal flats but the resulting sedimentary environment is similar. Both systems have the potential for progradation, tidal flats through accumulation from subtidal areas and overwash flats from an influx from supratidal areas.

Interestingly, the distinction between the two types of marsh found within the northeastern North Carolina estuarine system has some bearing on an old debate on the origin of marshes in general. One of the earliest theories on the origin of marshes was proposed by Mudge (1858). He found the peat in a section from a Massachusetts marsh to be dominated by high marsh grasses which **overlie** upland soils. This led him to conclude that marshes formed through the accumulation of high marsh peats which increased in thickness and advanced over the land as the land elevation changed relative to sea level.

Shaler (1886) contended that marshes originate when a protective energy barrier develops and allows mud to accumulate. The shallow mud flat is then colonized by marsh grasses which continue to build a muddy peat vertically until it reaches a thickness approaching the mean range of the tide. In 1911, Davis reported findings similar to those of Mudge and rejected Shaler's hypothesis. Johnson (1925) supported the Mudge-Davis hypothesis but suggested that Shaler's theory may account for the very beginnings of salt marshes. However, the location of initial growth would probably be inaccessible or destroyed by waves.

Shaler's hypothesis was given new credence in 1934 by Knight, who found what he termed a classic Shaler marsh near New Haven, Connecticut.

The stratigraphy of its lower units suggested that the marsh bed pioneered a developing mud flat. Later in its development it became a Mudge-Davis type marsh. Most recently, Redfield (1965, 1967, and 1972) documented Mudge-Davis and Shaler type marshes forming at the same time.

The two distinctly different types of modern marsh systems in northern North Carolina suggest that the two hypotheses are linked to two separate and distinct processes. Mainland type marshes appear to be entirely Mudge-Davis type marshes since no mud flats are required for the evolutionary succession of drowned wetland systems. The barrier island type marshes appear to be sandy versions of Shaler type marshes. Barrier islands are, for the most part, so dynamic that the vertical peat accumulation is limited and marshes do not have the time to migrate over upland areas.

Mainland Type Marshes and Estuarine Productivity

The significance of highly productive tidal marshes to estuarine ecology and productivity has been documented in tidal areas by a number of researchers: Odum (1961 and 1967), Darnell (1967), and Gosselink, Odum and Pope (1974), etc. The lack of regular tidal flushing, however, had led most researchers to assume that the irregularly flooded marshes of northeastern North Carolina are less important as sources of organic detritus than their tidal counterparts. Stiven and Plotecia (1976) estimated that only 10% of the annual productivity is flushed into the estuaries from irregularly flooded marshes. This compares to the 45% flushed from Georgia marshes (Teal 1962). However, the geometry and long

term evolutionary processes of the irregularly flooded marshes of northeastern North Carolina suggest that a different mechanism is responsible for introducing organic detritus into the estuarine system. Instead of being flushed from the marsh surface by regular tides, it appears that the detritus is introduced through erosion of the marsh edges.

Nearly all of the mainland type irregularly flooded marshes in the region are characterized by erosional peat scarp shorelines. These peat scarps range from approximately 1/3 meter to as much as 4 meters in height. Erosion rates of as high as 8 meters per year due to wave action have been reported for the more exposed marsh shorelines (Soil Conservation Service, 1974; Bellis, Riggs and O'Connor, 1975; Hardaway, pers. comm.). Even low energy marsh shorelines have an erosional morphology, as demonstrated by the Broad Creek system. In addition to wave exposure, shifting current patterns can have a dramatic impact on marsh erosion, as evidenced by the opening of Croatan Sound documented by Riggs and O'Connor (1974).

In northeastern North Carolina the loss of marsh to erosion along its edges has been offset by the vertical growth of the marsh surface in response to rising sea level. Through the process of vertical growth, the landward edge of the marsh migrates up and over the inorganic uplands. Vertical growth is accomplished where the annual productivity of the marsh exceeds the loss due to flushing, oxidation, reduction, or metabolism of the organic material produced, and the annual rise in sea level. Productivity rates have obviously been high enough for this to occur at least during the past 5,000 years.

A first approximation of the quantitative significance of the erosional mechanism for introducing organic detritus into the estuarine system is presented in Table 17. Even though all the parameters used in the approximation are conservative, the result of 3.2 tons per hectare per year, is two orders of magnitude greater than the 1.2 tons per hectare per year which results from flushing based on the data of Stiven and Plotecia (1976). Also somewhat surprising are the similarities between the erosional mechanism figures from this study and flushing mechanism figures reported for Georgia Spartina marsh and Florida mangrove marsh by de la Cruz (1973), which were 3.3 and 3.6 tons per hectare per year respectively.

A major difference between the two mechanisms which needs further study is the nature of the detritus supplied to the estuarine system. Flushed marshes primarily contribute the fresh annual crop of above ground marsh grass leaves. Erosional marshes contribute the accumulated storage of fossil organic material, which includes a significant percentage of below ground root and rhizome material which may be up to several thousand years old.

de la Cruz and Hackney (1977) have examined the energy content (KJ/g and KJ/g ash-free g) and nutritive values of the upper 40 centimeters of Juncus marsh peat in Mississippi. They found that energy content is somewhat higher for subsurface materials than for above ground material, while nutritive values were about the same. In addition, the peat below the living root zone (>20 cm below the marsh surface) has higher ash-free energy and nutritive values, with the exception of phosphorous, than peat from the living root zone (upper 20 cm).

Table 17. Estimates of Organic Detritus Introduced into the Estuarine System through Marsh Shoreline Erosion of Irregularly Flooded Mainland Type Marshes

PARAMETERS

Miles of shoreline	880 (Riggs et. al., 1978)
Average erosion rate	3 feet/year (Riggs et. al., 1978)
Average peat thickness	2 feet (personal observation)
Average organic content	40% (estimated from values reported by Dolman & Beal, 1967; Campbell, 1979; & Pestrong, 1969).
Average density	29 Pcf (estimated from values reported by Dolman & Beal, 1967; Campbell, 1979; Pestrong, 1969; & U.S.D.I., 1957)
Irregularly flooded marsh area in N. C.*	50,588 hectares (Wilson, 1962)

RESULTS:

Total organic detritus entering the northeastern North Carolina estuaries as a result of shoreline erosion*	323 million pounds/year
Mechanism efficiency, organic material entering per unit of marsh	3.2 tons/hectare/year

COMPARISONS:

Total organic detritus entering the northeastern North Carolina estuaries as a result of flushing* based on 10% annual productivity assumed by Stiven and Plotecia (1976) and a mean annual productivity value of 868 g/m ² /year for <u>Juncus roemerianus</u> based on actual measurements by Foster (1968), Stroud & Cooper (1969), Williams & Murdoch (1972), and Waits (1967).	97 million pounds/year 1.0 tons/hectare/year
Organic detritus entering Georgia estuaries as a result of tidal flushing from <u>Spartina alterniflora</u> marshes (de la Cruz, 1973).	3.4 tons/hectare/year
Organic detritus entering Florida estuaries as a result of tidal flushing from mangrove marshes (de la Cruz, 1973).	3.6 tons/hectare/year

* Does not include the Currituck Sound area.

This, they reasoned, resulted from the absorption, adsorption, and trapping of dissolved nutrient materials by the dead tissues of the lower peat. If this is a universal process, then it would suggest that the storage phase which mainland type marsh systems undergo actually upgrades the peat as a source of detritus.

Interestingly, two of the most significant and unique characteristics of the region, the low slopes on the interstream divides and lack of a regular astronomical tidal flux, are essential to the maintenance of the migrating marshes. The low slopes allow rapid expansion of the landward edges of the marshes, while the lack of regular tides prevents a build-up of tidal flats which would prevent or at least reduce the erosion of the estuarine shoreline.

S U M M A R Y A N D C O N C L U S I O N S

1. The Broad Creek embayment, tidal creek, and irregularly flooded marsh system has developed within the last 5,000 to 6,000 years in response to a variable but continuous rise in sea level.
2. Seven stratigraphic units were identified within the study area. Units 1 and 2 are found essentially throughout the study area, Units 3 and 4 are found associated primarily with the irregularly flooded marsh system and Units 5 through 7 are associated with the embayment and tidal creek system.
 - a. Unit 1 is an iron stained thin bedded clean sandy unit which was apparently deposited during the mid-Wisconsin high stand of sea level. During the late Wisconsin glacial period, the unit underwent dissection and pedogenesis. The relief and soil horizon formed on this unit has provided the basement for, and influenced the deposition of subsequent units.
 - b. Unit 2 overlies Unit 1 everywhere except where Unit 1 forms the modern soil of the upland forests. The Unit consists of tan muddy sand characterized by interspersed vertically oriented grass material. This unit is still forming today along the transition zone between the forested uplands and the irregularly flooded marsh.
 - c. Unit 3 is a fresh marsh peat 1/3 to 2 meters thick which typically overlies Unit 2 and which is characterized by a dark amorphous aggregate dominated organic fraction. The

fresh marsh which produced the unit dominated the study area between approximately 2,500 BP and 1,000 BP. After that time brackish conditions had become so dominant, fresh systems were almost eliminated.

- d. Unit 4 is a muddy brackish marsh peat averaging 1 to 1½ meters thick which typically overlies Unit 3 peat or Unit 2 muddy sand. The peat is characterized by an organic fraction dominated by fine vascular and epidermal grass fragments. The brackish marsh which produced the unit first developed along the southeastern portion of the study area approximately 1,500 years ago. By 1,000 BP it had become the dominant marsh type within the study area. This marsh type continues to be dominant at the present.
- e. Unit 5 is a highly organic rich (organic material generally makes up 77% of the coarse fraction by volume) allochthonous mud which is confined to the tidal creek system and southwestern facing embayments within the Broad Creek embayment.
- f. Unit 6 is an organic rich mud filling the relict creek channel extending down the center of the Broad Creek embayment. The rate of permanent mud deposition, which began approximately 1,700 years ago, appears to be related to the rate of sea level rise.
- g. Unit 7 is a clean fine to medium grained bar sand. Within the Broad Creek embayment, Unit 7 bar sands form a thin veneer over the muddy sand of Unit 2. Bar sands also form a thin veneer over peat within the small embayments with a northeast exposure along the western shoreline of Broad

Creek. A much thicker (>1 m) accumulation of bar sand forms the large bay mouth bar at the southern end of the study area. Here Unit 7 overlies Unit 6 muds.

3. Stratigraphic relationships, sediment distribution patterns, and SCUBA reconnaissance indicate that classical processes of tidal sedimentation are not operating within the Broad Creek system. Instead of the typical tide or mud flats characterized by a gently sloping intertidal geometry and regularly flooded marsh systems, the Broad Creek system is characterized by a step shoreline geometry. Major sedimentation processes operating within the study area today include the following:
 - a. Permanent deposition of suspended sediment is occurring during normal energy conditions in the relict stream channel extending down the center of the Broad Creek embayment.
 - b. Deposition of suspended sediment is occurring on the marsh surface during high wind tides, particularly along levees adjacent to the shorelines.
 - c. Sand sized sediment is being eroded from and transported in a southerly direction along the relatively high energy Roanoke Sound shoreline. This sediment is being deposited on a subaqueous baymouth bar at the southern end of the Broad Creek embayment.
 - d. Unit 2 muddy sand is being exposed on the bay shelves within Broad Creek as the less resistant overlying peat units are eroded away leaving a thin deposit of lag sands. The lag sands are being winnowed and reworked into thin shelf bars on the bay shelves.

- e. Biocorrosion and wave erosion during low wind tides is producing undercut peat scarp marsh shorelines.
 - f. The marsh is growing upward and landward in response to rising sea level.
4. The introduction of new sediment into the major portion of the study area is confined to 1) silt, clay, and detrital organic material which moves into the system as suspended sediment, and 2) an autochthonous organic accumulation on the surface and within the root zone of the marsh. Within the central basin permanent deposition of the imported suspended sediment only occurs at a critical depth determined by the energy levels within the system. New coarse sediment within the study area is confined to the baymouth bar at the southern end of Broad Creek.
5. Unlike the gently sloping surfaces of regularly flooded tidal marsh systems, the surface of the irregularly flooded marsh within the study area is essentially a horizontal plane. Nearly all of the marsh surface has an elevation of 10 to 15 centimeters above normal water level and is colonized by Juncus roemerianus. Plant communities, which comprise the remaining portions of the marsh, result from relief on this plane and include the following:
- a. A narrow (1 to 5 m. wide) gently sloping intertidal zone occurs along the bay shoreline and is colonized by dwarfed Spartina alterniflora. The slope is produced by a gentle down warping of the marsh root mat in response to being undercut along the peat scarp shorelines.
 - b. A series of narrow (2 to 10 m. wide) low ($\frac{1}{2}$ m. high) levees occur just inland from the intertidal zone. Poorly developed

levees colonized by Iva frutescens occur along the low energy tidal creek channels. Better developed muddy levees occur along the Broad Creek embayment and are colonized by Spartina cynosroides.

- c. A broad low levee colonized by Spartina patens occurs along the more exposed southeastern margin of the study area.
6. The Broad Creek system is undergoing a similar evolutionary response to rising sea level as the larger scale components of the northeastern North Carolina estuarine system. Sediment distribution patterns, basin geometry, and shoreline morphology are very similar in both scales of features within the region. This is in contrast to similar sized features in estuarine systems influenced by a greater astronomical tidal range.
7. The irregularly flooded marsh in the study area has a distinctly different origin and evolution than that reported in the literature for irregularly flooded marshes found on the estuarine side of the barrier islands in northeastern North Carolina. Within the study area, the origin and evolution of the marsh system is closely tied to the relict topography of the mainland, whereas the barrier island marsh system is closely tied to the modern physical processes of the barrier island. Consequently it is important to differentiate the mainland type irregularly flooded marshes from the barrier island type irregularly flooded marshes.
8. The apparent undercut erosional marsh shoreline and erosional evolutionary history of the embayment are inconsistent with the lack of erosion indicated by aerial photography between 1945 and 1974. It is hypothesized that the thick peat units are undergoing

a lateral flow in response to continued organic accumulation with time. This results in a steady state shoreline in which the flow is apparently keeping pace with erosion in the Broad Creek system.

9. Marsh shorelines are erosional not only within the study area but throughout the northeastern North Carolina estuarine system. The magnitude of this erosion suggests that this mechanism might be an important alternative means of introducing stored organic detritus into the estuarine systems where regular tidal flushing is not significant. Preliminary calculations indicate that the amount of organic detritus entering the North Carolina estuarine system through marsh shoreline erosion, is very similar to amounts reported in the literature entering the Georgia estuaries through regular tidal flushing.
10. A major change occurs from tidal flat geometries and sedimentation processes to the step geometry and associated sedimentation processes, as described in Broad Creek, where the tidal range is $\frac{1}{2}$ meter or less. Since this natural break falls within the microtidal category of the Davies (1964) classification, it is proposed that estuarine systems with a tidal range of $\leq \frac{1}{2}$ meter be differentiated from the microtidal subdivision. The new proposed category is called the "nanotidal" system.

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APPENDIX 1

 C_{14} Data

SAMPLES C₁₄ AGE DATED

Teledyne Isotopes Sample Number	This Study Sample Number	Sample Material	Mean Sample Depth Below Sea Level (Meters)	-C ₁₄ δ	Age In Years B.P.
1-8987	B-1	Shell	2.2	55±10	455±85
1-8988	C15-5	Wood	2.4	268±8	2505±90
1-8989	C75-2	Peat	0.5	39±9	320±80
1-8990	C75-10	Peat	2.9	484±7	5315±110
1-8991	C72-5	Peat	1.3	162±10	1420±95
1-8999	C74-2	Peat	0.4	39±11	320±95
1-9000	C74-9	Wood	NOT ANALYZED - CONTAMINATION		
1-9182	C72-2	Peat	0.4	25	210
1-9181	C75-4	Peat	1.1	96±9	810±80
1-9183	C77-6	Peat	1.5	187±9	1665±85
1-9206	C76-8	Peat	2.3	197±9	1765±85
1-9207	C75-7	Peat	2.0	221±8	2005±85
1-9208	C55-4	Woody Peat	2.3	357±8	3545±100
1-9237	C85-5	Peat	1.1	139±9	1200±85
1-9254	C72-3	Peat	0.6	24	195
1-9251	C75-5	Peat	1.4	137±8	1185±85
1-9252	C72-4	Peat	1.0	24±11	195±90
1-9253	C75-8	Peat	2.3	248±10	2290±110

APPENDIX 2

Surface Sample Data

SAMPLE NO.	Sample Depth Meters MSL	Weight $\geq 4\phi$	COARSE FRACTION ($<4\phi$)												
			INORGANIC MATERIAL						SHELL			PLANT MATERIAL			
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals *	Fragile Shell Hash	Robust Shell Hash	X Foraminifera	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates	Wood

CENTRAL BASIN SAMPLES (UNIT 6 ORGANIC RICH MUDS)

S4-1	-1.2	80%	Fine	Coarse	Mod.	T%	Mica	OH.	1%	0	0	20%	60%	35%	5%	T%
S6-1	-1.1	45%	Fine	Medium	Well	T%	Mica	OH.	T%	0	0	7%	50%	40%	10%	T%
T1-1-2	-1.2	64%	Fine	Coarse	Well	0	Mica		T%	0	0	15%	10%	40%	40%	10%
T6-1-1	-1.5	77%	V. Fine	Granule	M. Well	T%	Opaque Heavies	Mica, GL.	1%	0	0	45%	90%	T%	10%	T%
T14-1-1	-1.7	93%	Fine	Med.	V. Well	T%	Mica	OH.	1%	0	(M)	25%	90%	5%	5%	T%
T20-4-1	-1.7	67%	Fine	V. Coarse	Well	T%	Mica		T%	0	0	10%	99%	T%	T%	T%
T20-4-2	-1.7	33%	Fine	V. Coarse	M. Well	T%	Mica	OH.	T%	0	0	7%	T%	50%	50%	T%
T20-5-1	-1.7	81%	Fine	Med.	V. Well	0	Mica	GL.	T%	0	0	20%	97%	3%	0	T%
T20-5-2	-1.7	92%	Fine	Granule	M. Poor	T%	Mica	OH.	T%	0	0	40%	80%	2%	18%	T%
T31-1-1	-1.5	88%	V. Fine	V. Coarse	V. Well	T%	Mica	OH.	T%	0	0	40%	98%	2%	T%	T%
731-2-1	-1.5	93%	Fine	V. Coarse	Well	T%	Mica	OH.	1%	0	0	20%	97%	3%	T%	0
C15-1	-1.2	73%	V. Fine	Granule	Poor	T%	Mica	OH.	T%	0	0	50%	88%	10%	2%	0
C17-1	-1.8	58%	Fine	V. Coarse	M. Well	T%	Mica	OH.	2%	0	0	7%	94%	3%	3%	0
C55-1	-1.7	93%	Fine	Coarse	M. Well	1%	Mica	OH.	7%	0	0	15%	25%	55%	20%	0

* OH. - Opaque Heavies
GL. - Glauconite

X (M) - Milioline

SAMPLE NO.	Sample Depth Meters MSL	Weight % >4φ	COARSE FRACTION (<4φ)													
			INORGANIC MATERIAL						SHELL			PLANT MATERIAL				
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals *	Fragile Shell Hash	Robust Shell Hash	Foraminifera ^x	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates	Wood	Seeds

BAY SHELF SAMPLES (UNIT 2 MUDDY SAND)

S15-2	-1.7	21%	Fine	Pebble	V. Poor	8%	Opaque Heavies	Mica, Fe Agg., GL.	1%	4%	(C)	35%	45%	45%	10%	T%
S17-1	-1.5	20%	Fine	Granule	Poor	5%	Opaque Heavies	Mica	T%	0	0	7%	99%	T%	T%	0
S18-1	-1.1	33%	Fine	V. Coarse	Poor	T%	Opaque Heavies		T%	T%	0	20%	99%	0	T%	0
S19-1	-1.3	42%	Fine	Pebble	Mod.	T%	Opaque Heavies	Mica	T%	T%	(C)	30%	99%	T%	T%	0
S23-1	-1.1	25%										15%				
S25-3	-1.4	23%	Fine	Coarse	Well	T%	Opaque Heavies		0	T%	0	15%	60%	10%	30%	T%
T2-1-1	-1.3	19%	Fine	Granule	Poor	1%	Opaque Heavies	Mica	1%	4%	0	5%	99%	T%	1%	0
T13-3-1	-1.4	25%	Fine	Coarse	M. Well	T%	Opaque Heavies	Mica, Fe Agg.	T%	0	0	5%	70%	25%	5%	0
T20-1-3	-1.1	30%	U. Fine	Coarse	Well	T%	Opaque Heavies	Mica	0	0	0	8%	99%	T%	T%	0
T20-2-1	-1.1	17%	Medium	V. Coarse	M. Well	2%	Opaque Heavies	Mica	0	0	0	5%	99%	T%	T%	T%
T22-1-1	-1.2	33%	L. Med.	V. Coarse	M. Well	1%	Opaque Heavies	Mica	T%	0	0	3%	99%	T%	1%	0
T26-3-1	-1.1	17%	L. Med.	V. Coarse	M. Well	2%	Opaque Heavies	Mica	T%	0	0	2%	70%	20%	10%	T%
T5 COM	0	20%	Fine	Granule	Mod.	10%	Opaque Heavies	Mica, Fe Agg.	0	0	(C)	20%	99%	1%	0	0
C 67-1	0	17%	Fine	Coarse	M. Well	3%	Opaque Heavies		0	0	0	35%	90%	2%	8%	0

BAY SHELF FE STAINED SEDIMENT SAMPLES (UNIT 1 IRON STAINED CLEAN SAND)

S14-1	-1.1	5%	Fine	Pebble	Poor	60%	Opaque Heavies	GL.	1%	2%	0	T%	99%	T%	T%	T%
S15-1	-1.1	5%	Coarse	Pebble	Mod.	2%	Mica	OH.	1%	3%	(C)	1%	99%	1%	0	0
T33-2-1	-1.8	5%	L. Med.	Pebble	V. Poor	25%	Opaque Heavies	Mica	T%	0	(C)	1%	99%	1%	0	T%
C28-1	-1.1	5%	Fine	Granule	M. Poor	99%	Opaque Heavies		0	0	0	3%	100%	0	0	0

* Fe Agg. - Iron Aggregates

GL. - Glauconite

OH. - Opaque Heavies.

^x (C) - Planispirally Coiled

SAMPLE NO.	Sample Depth Meters MSL	Weight $>4\phi$	COARSE FRACTION ($<4\phi$)												
			INORGANIC MATERIAL						SHELL			PLANT MATERIAL			
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals *	Fragile Shell Hash	Robust Shell Hash	X Foraminifera	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates	Wood

SHELF BAR SAMPLES (UNIT 7 CLEAN SAND)

S2-1	-1.1	11%	Fine	Granule	Poor	7%	Opaque Heavies	Mica	1%	0	0	3%	80%	10%	10%	0
S18-3	-1.2	6%	Fine	Pebble	V. Poor	1%	Opaque Heavies		T%	0	0	5%	95%	5%	T%	0
S21-1	-1.1	4%	Fine	Granule	M. Well	10%	Opaque Heavies	Mica, Fe Agg.	T%	0	0	T%	75%	20%	5%	0
S25-1	-1.4	3%	Fine	Granule	Mod.	T%	Opaque Heavies		T%	0	0	T%	100%	0	0	0
T13-2-1	-1.0	4%	Fine	Medium	V. Well	1%	Opaque Heavies	Mica	T%	0	0	T%	99%	0	T%	0
T16-1-1	-0.8	2%	Fine	Medium	Well	1%	Opaque Heavies		T%	0	0	T%	65%	10%	25%	0
T16-1-1A	-0.8	7%	Fine	Coarse	V. Well	T%	Opaque Heavies	Mica	0	0	(M)	8%	50%	15%	35%	T%
T20-1-1	-1.1	6%	Fine	V. Coarse	Well	3%	Opaque Heavies	Mica, GL.	0	0	0	1%	80%	15%	5%	0
T20-3-1	-1.1	7%	L. Med.	V. Coarse	M. Well	1%	Opaque Heavies	Mica	T%	0	0	T%	99%	T%	T%	0
T20-3-2	-1.1	9%	Fine	Pebble	M. Well	T%	Opaque Heavies	Mica	T%	0	0	10%	85%	T%	15%	0
T26-1-1	-1.4	9%	Med.	Coarse	M. Well	2%	Opaque Heavies		T%	0	(M)	5%	98%	T%	2%	0
T31-3-1	-1.4	5%	Med.	Coarse	Well	1%	Opaque Heavies	Mica	T%	0	(M)	T%	20%	80%	T%	0
C16-1	-1.4	4%	Med.	Pebble	V. Poor	T%	Opaque Heavies	Mica	0	0	0	T%	33%	33%	33%	0
S23-3	-1.0	4%	Fine	Granule	M. Well	T%	Opaque Heavies		1%	1%	0	10%	80%	10%	10%	0

BAY MOUTH BAR SAMPLES (UNIT 7 CLEAN SAND)

S1-1	-1.0	6%	Med.	Granule	M. Well	T%	Opaque Heavies	Mica	T%	0	0	1%	99%	T%	T%	0
S1-2	0	1%	Med.	Coarse	Well	20%	Opaque Heavies		T%	0	0	0	0	0	0	0
OS-1	-1.0	3%	U. Fine	V. Coarse	M. Well	3%	Opaque Heavies	Mica	T%	0	(M)	T%	99%	1%	0	0
T33-1-1	-1.1	1%	L. Med.	Granule	M. Poor	10%	Opaque Heavies	GL.	T%	0	0	0	0	0	0	0
T34-2-1	-1.2	4%	Fine	Granule	M. Poor	7%	Opaque Heavies	Mica	T%	0	0	T%	99%	T%	T%	0
C29-1	-1.0	2%	Med.	Granule	Poor	2%	Opaque Heavies	Mica	T%	0	0	T%	100%	0	0	0

* Fe Agg. - Iron Aggregates

GL. - Glauconite

x (M) - Milioline

SAMPLE NO.	Sample Depth Meters MSL	Weight $\geq 4\phi$	COARSE FRACTION ($<4\phi$)													
			INORGANIC MATERIAL						SHELL			PLANT MATERIAL				
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals*	Fragile Shell Hash	Robust Shell Hash	X Foraminifera	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates	Wood	Seeds

IRREGULARLY FLOODED BRACKISH MARSH SAMPLES (UNIT 4 BROWN FIBROUS PEAT - MUDDY)

M3-1	0	79%	Fine	Coarse	Well	0	Mica	Fe Agg., GL, OH.	0	0	0	85%	100%	0	0	0
M3-2	0	85%					Mica	Fe Agg.	1%	0	(C)	99%	100%	0	0	0
M3-3	0	87%	Fine	V. Coarse	Well	0	Mica	Fe Agg.	0	0	0	95%	100%	0	0	0
M3-4	0	86%	Fine	Coarse	M. Well	1%	Mica	Fe Agg., OH.	0	0	0	95%	100%	0	0	0
M2-3	0	84%					Mica	Fe Agg.	0	0	(C)	100%	100%	0	0	0
C70-1	0	78%	V. Fine	Med.	V. Well	T%	Mica	Fe Agg.	0	0	0	99%	99%	T%	T%	0
C71-1	0	60%	Med.	Coarse	M. Poor	25%	Mica		0	0	0	100%	99%	1%	0	0
C72-1	-	86%	V. Fine	Med.	V. Well	T%	Mica	Fe Agg., OH.	0	0	(C)	99%	100%	0	0	0
C73-1	0	66%					Mica		0	0	(C)	100%	100%	0	0	0
C74-1	0	65%	Med.	Coarse	M. Well	T%	Fe Aggregates	Mica, OH.	0	0	(C)	98%	100%	0	0	0
C75-1	0	65%	Med.	Coarse	M. Well	0	Mica		0	0	(C)	100%	100%	0	0	0
C76-1	0	87%	Fine	Pebble	M. Poor	T%	Mica	Fe Agg., OH.	0	0	(C)	85%	99%	T%	0	0
C77-1	0	90%	V. Fine	V. Coarse	M. Well	T%	Mica	Fe Agg.	0	0	0	85%	100%	T%	0	0
C-80-1	0	95%	Fine	Med.	V. Well	0	Fe Aggregates	Mica, GL., OH.	T%	0	(C)	95%	95%	5%	T%	T%

IRREGULARLY FLOODED BRACKISH MARSH SAMPLES (UNIT 4 BROWN FIBROUS PEAT - CLEAN)

S7-1		23%	U. Fine	Coarse	M. Well	T%	Mica	OH.	0	0	0	80%	100%	0	0	0
C68-1	0	33%	L. Med.	V. Coarse	Mod.	T%	Opaque Heavies		0	0	0	90%	99%	T%	0	T%

IRREGULARLY FLOODED BRACKISH MARSH SAMPLES (UNIT 4 BROWN FIBROUS PEAT - SANDY, MUDDY)

C78-1	0	88%	U. Fine	V. Coarse	Poor	1%	Mica	Fe Agg., OH.	0	0	(C)	35%	99%	T%	T%	0
M2-4	0	45%	Fine	Coarse	Well	3%	Opaque Heavies	Mica, Fe Agg., GL.	0	0	(C)	40%	100%	0	0	0

* Fe Agg. - Iron Aggregates
GL. - Glauconite
OH. - Opaque Heavies

X (C) - Planispirally Coiled

SAMPLE NO.	Sample Depth Meters MSL	Weight % >4φ	COARSE FRACTION (<4φ)												
			INORGANIC MATERIAL						SHELL			PLANT MATERIAL			
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals *	Fragile Shell Hash	Robust Shell Hash	Foraminifera	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates	Wood

TIDAL CREEK SHOAL SAMPLES (UNIT 5 HIGHLY ORGANIC RICH MUD)

S10-1	-1.1	73%	Med.	V. Coarse	Mod.	T%	Opaque Heavies	Mica		0	0	0	75%	30%	60%	10%	T%
S11-1	-1.2	96%	V. Fine	Coarse	Well	T%	Mica	OH.		T%	0	0	75%	75%	25%	T%	T%
UBC1-1	-0.6	91%	U. Fine	U. Fine	V. Well	0	Mica	GL.		0	0	0	95%	90%	10%	T%	0
T26-2-1	-1.5	94%	Fine	Coarse	M. Well	T%	Mica	OH.		T%	0	0	65%	85%	6%	9%	T%

TIDAL CREEK CHANNEL SAND (UNIT 7 CLEAN SAND)

UBC1-2	-0.6	1%	U. Fine	Granule	M. Well	20%	Opaque Heavies	Mica		T%	0	0	T%	0	100%	0	T%
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* OH. - Opaque Heavies
GL. - Glauconite

APPENDIX 3

Core Sample Data

SAMPLE NO.	Sample Depth Meters MSL	Weight $>4\phi$	COARSE FRACTION ($<4\phi$)												
			INORGANIC MATERIAL						SHELL			PLANT MATERIAL			
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals %	Fragile Shell Hash	Robust Shell Hash	Foraminifera	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates	Wood

UNIT 1 IRON STAINED CLEAN SAND - UNIT SURFACE

C15-5	-2.2	8%	Fine	Granule	M. Well	95%	Opaque Heavies		0	0	0	15%	30%	T%	70%	0
C16-6	-2.4	3%	Fine	V. Coarse	M. Well	60%	Opaque Heavies	GL.	0	0	0	2%	100%	0	0	0
C18-5	-1.9	5%	Fine	Granule	Poor	95%	Opaque Heavies		0	0	0	7%	80%	0	20%	0
C26-7	-2.4	5%	Fine	Coarse	M. Well	95%	Opaque Heavies	Mica	0	0	0	15%	95%	1%	4%	0
C53-4	-2.4	1%	Fine	Medium	V. Well	1%	Opaque Heavies	Mica, GL.	0	0	0	5%	99%	T%	T%	0
C67-9	-1.2	3%	Fine	V. Coarse	M. Well	1%	Opaque Heavies		0	0	0	3%	100%	T%	0	0
C70-12	-3.0	11%	V. Fine	Granule	Mod.	90%	Opaque Heavies		0	0	0	2%	50%	50%	T%	0
C71-15	-2.6	3%	Fine	Granule	V. Poor	90%	Opaque Heavies		0	0	0	1%	100%	0	0	0
C72-10	-2.4	7%	L. Med.	Granule	M. Poor	90%	Opaque Heavies		0	0	0	8%	99%	T%	T%	0
C73-8	-2.1	4%	Fine	Granule	M. Poor	80%	Opaque Heavies		0	0	0	5%	80%	18%	2%	0
C75-13	-3.2	8%	Fine	Granule	M. Poor	5%	Opaque Heavies	Mica	0	0	0	5%	85%	15%	0	0
C78-11	-2.4	5%	Med.	V. Coarse	M. Poor	90%	Opaque Heavies		0	0	0	2%	0	T%	99%	0
C74-8	-1.4	22%	Fine	Granule	M. Well	3%	Opaque Heavies		0	0	0	10%	60%	T%	40%	0
C76-14	-3.3	17%	Med.	Pebble	V. Poor	30%	Opaque Heavies		0	0	0	T%	99%	T%	T%	0

TRANSITION SAMPLES - UNIT 1-UNIT 2

C26-6	-2.1	19%	Fine	Coarse	M. Well	30%	Opaque Heavies		0	0	0	30%	65%	20%	15%	0
C74-9	-1.5	30%	Med.	Coarse	M. Well	3%	Opaque Heavies		0	0	0	45%	10%	0	90%	0
C66-1	0	29%	Fine	V. Coarse	M. Poor	T%	Opaque Heavies		0	0	0	30%	15%	5%	80%	0
C66-2	-0.1	18%	Fine	V. Coarse	Mod.	T%	Opaque Heavies		0	0	0	35%	29%	30%	40%	0

* GL. - Glauconite

SAMPLE NO.	Sample Depth Meters MSL	Weight % >4φ	COARSE FRACTION (<4φ)													
			INORGANIC MATERIAL						SHELL			PLANT MATERIAL				
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals *	Fragile Shell Hash	Robust Shell Hash	Foraminifera	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates	Wood	Seeds
UNIT 1 IRON STAINED CLEAN SAND - UNIT SUBSURFACE																
C18-6	-2.2	6%	Fine	Granule	V. Poor	90%	Opaque Heavies		0	0	0	12%	99%	0	T%	0
C18-8	-2.5	3%	Fine	V. Coarse	V. Poor	100%	Opaque Heavies	Mica	0	0	0	5%	90%	0	10%	0
C53-5	-2.7	1%	U. Fine	Coarse	V. Well	2%	Opaque Heavies	Mica, GL,	0	0	0	3%	100%	0	0	0
C68-4	-0.3	14%	Fine	V. Coarse	Well	2%	Opaque Heavies		0	0	0	15%	40%	5%	55%	0
C66-5	-.42	13%	Fine	V. Coarse	Mod.	20%	Opaque Heavies		0	0	0	15%	40%	5%	55%	0
C70-14	-3.2	2%	Fine	V. Coarse	Mod.	95%	Opaque Heavies		0	0	0	T%	10%	90%	0	0
C71-16	-2.8	3%	Fine	Granule	V. Poor	100%	Opaque Heavies		0	0	0	T%	100%	0	0	0
C72-11	0	3%	U. Fine	V. Coarse	M. Well	90%	Opaque Heavies	GL.	0	0	0	1%	80%	0	20%	0
C73-9	-2.3	4%	Fine	Granule	Poor	100%	Opaque Heavies		0	0	0	5%	90%	0	10%	0
C73-11	-2.5	4%	Fine	V. Coarse	M. Poor	100%	Opaque Heavies		0	0	0	1%	0	0	100%	0
C75-15	-3.6	4%	Medium	Granule	Mod.	100%	Opaque Heavies	Mica	0	0	0	3%	98%	0	2%	T%
C78-13	-2.7	2%	Medium	Pebble	V. Poor	99%	Opaque Heavies		0	0	0	0	0	0	0	0
C77-12	-2.4	17%	L. Med.	Granule	M. Poor	30%	Opaque Heavies		0	0	0	1%	99%	1%	0	0

* GL. - Glauconite

SAMPLE NO.	Sample Depth Meters MSL	Weight $\geq 4\phi$	COARSE FRACTION ($<4\phi$)												
			INORGANIC MATERIAL						SHELL		PLANT MATERIAL				
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals*	Fragile Shell Hash	Robust Shell Hash	Foraminifera	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates	Wood

UNIT 2 MUDDY SAND - UNIT SURFACE

C15-2	-1.5	22%	Fine	V. Coarse	M. Well	1%	Opaque Heavies		0	0	0	20%	80%	15%	5%	0
C16-2	-1.6	27%	Fine	Granule	M. Poor	T%	Opaque Heavies		0	0	0	10%	25%	10%	20%	0
C17-5	-2.9	24%	U. Fine	V. Coarse	Mod.	25%	Opaque Heavies	Fe Agg.	0	0	0	10%	0	75%	25%	0
C18-3	-1.4	28%	Fine	Pebble	V. Poor	T%	Opaque Heavies		0	0	0	15%	98%	2%	T%	0
C26-2	-1.3	32%	U. Fine	Coarse	Well	T%	Opaque Heavies	Mica	0	0	0	15%	100%	T%	0	0
C53-1	-1.7	30%	Fine	V. Coarse	Well	2%	Opaque Heavies		T%	0	0	10%	20%	80%	T%	0
C55-5	-2.4	25%	Fine	V. Coarse	Well	2%	Opaque Heavies		0	0	0	5%	60%	40%	0	0
C67-2	-0.1	22%	Medium	V. Coarse	Mod.	2%	Opaque Heavies		0	0	0	8%	99%	T%	1%	0
C70-9	-2.6	30%	L. Med.	Granule	M. Poor	3%	Opaque Heavies		0	0	0	10%	4%	90%	6%	0
C72-6	-1.5	29%	U. Fine	V. Coarse	Mod.	T%	Opaque Heavies		0	0	0	17%	95%	4%	1%	0
C75-12	-3.1	20%	Fine	Ganule	M. Well	3%	Opaque Heavies	Mica	0	0	0	10%	90%	10%	0	T%
C76-10	-2.5	29%	Medium	Pebble	V. Poor	0	Opaque Heavies		0	0	0	2%	0	60%	40%	0
C78-7	-1.5	26%	Medium	V. Coarse	Mod.	5%	Opaque Heavies		0	0	0	3%	90%	2%	8%	0
C85-6	-1.2	22%	U. Fine	V. Coarse	M. Well	T%	Opaque Heavies		0	0	0	20%	99%	T%	1%	0
C29-4	-1.8	11%	Fine	Pebble	V. Poor	1%	Opaque Heavies		0	0	0	4%	10%	90%	T%	T%
C77-8	-1.8	12%	L. Med.	Granule	V. Poor	5%	Opaque Heavies		0	0	0	5%	40%	60%	0	0

* Fe Agg. - Iron Aggregates

SAMPLE NO.	Sample Depth Meters MSL	Weight % >4φ	COARSE FRACTION (<4φ)												
			INORGANIC MATERIAL						SHELL			PLANT MATERIAL			
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals *	Fragile Shell Hash	Robust Shell Hash	Foraminifera	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates	Wood

UNIT 2 MUDDY SAND - UNIT MIDDLE

C15-3	-1.8	19%	Fine	Granule	Mod.	T%	Opaque Heavies			0	0	0	15%	95%	3%	2%	0
C16-3	-1.9	25%	Fine	Pebble	Mod.	T%	Opaque Heavies			0	0	0	2%	99%	T%	0	0
C26-3	-1.5	32%	Fine	Coarse	Well	T%	Opaque Heavies	Mica		0	0	0	18%	100%	0	0	0
C26-4	-1.7	26%	Fine	V. Coarse	Well	T%	Opaque Heavies			0	0	0	15%	95%	1%	4%	0
C67-3	-0.2	29%	Fine	V. Coarse	Mod.	2%	Opaque Heavies	Fe Agg.		0	0	0	15%	98%	T%	2%	0
C67-6	-0.7	15%	Fine	V. Coarse	M. Well	1%	Opaque Heavies			0	0	0	3%	100%	T%	0	0
C68-6	-0.5	18%	L. Med.	Coarse	M. Well	10%	Opaque Heavies			0	0	0	25%	85%	8%	7%	0
C68-9	-0.8	21%	Fine	V. Coarse	Mod.	8%	Opaque Heavies			0	0	0	8%	92%	3%	5%	0
C71-13	-2.0	23%	Fine	Granule	Poor	6%	Opaque Heavies			0	0	0	5%	99%	T%	0	0
C74-3	-0.4	24%	Medium	Coarse	M. Well	5%	Opaque Heavies			0	0	0	7%	90%	8%	2%	0
C74-5	-0.8	24%	Fine	V. Coarse	M. Well	2%	Opaque Heavies			0	0	0	10%	90%	9%	1%	0
C74-7	-1.1	27%	Medium	V. Coarse	Mod.	2%	Opaque Heavies			0	0	0	10%	70%	10%	20%	0
C55-6	-2.6	10%	Fine	V. Coarse	Mod.	2%	Opaque Heavies			0	0	0	5%	70%	30%	0	0
C78-9	-2.0	7%	Medium	V. Coarse	M. Poor	10%	Opaque Heavies			0	0	0	2%	100%	T%	0	0
C29-5	-1.9	7%	Fine	V. Coarse	Mod.	1%	Opaque Heavies			0	0	0	2%	99%	0	T%	0

UNIT 2 MUDDY SAND - UNIT BASE

C26-5	-1.8	24%	Fine	Coarse	Well	T%	Opaque Heavies			0	0	0	18%	95%	3%	2%	0
C29-7	-2.1	18%	Fine	V. Coarse	Mod.	1%	Opaque Heavies			0	0	0	2%	99%	0	T%	0
C77-9	-2.1	20%	Medium	Granule	V. Poor	3%	Opaque Heavies			0	0	0	5%	70%	30%	0	0
C85-8	-1.6	26%	Fine	V. Coarse	Well	1%	Opaque Heavies			0	0	0	10%	99%	0	T%	0
C80-12	-3.4	23%	U. Fine	V. Coarse	Mod.	20%	Opaque Heavies			0	0	0	2%	99%	1%	0	0
C53-3	-2.1	20%	Fine	V. Coarse	M. Well	T%	Opaque Heavies			0	0	0	10%	90%	10%	T%	0
C78-10	-2.3	8%	L. Med.	Granule	M. Poor	T%	Opaque Heavies			0	0	0	T%	99%	T%	0	0

* Fe Agg. - Iron Aggregates

SAMPLE NO.	Sample Depth Meters MSL	Weight $\geq 4\phi$	COARSE FRACTION ($<4\phi$)											
			INORGANIC MATERIAL						SHELL			PLANT MATERIAL		
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals	Fragile Shell Hash	Robust Shell Hash	Foraminifera ^x	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates

UNIT 3 DARK AGGREGATE PEAT

S16-1	-1.2	28%	Fine	Granule	Poor	T%	Mica		T%	0	(C)	90%	60%	40%	T%	T%
C18-1	-1.1	47%	Fine	Granule	M. Poor	T%	Opaque Heavies		0	0	0	75%	10%	90%	T%	0
C80-5	-0.9	4%	----	-----	-----	---	--		0	0	0	75%	10%	90%	T%	0
C75-6	-1.5	34%	Med.	Med.	V. Well	0	--		0	0	0	100%	0	98%	2%	T%
C70-8	-1.5	44%	Fine	V. Coarse	Mod.	1%	Opaque Heavies		0	0	0	85%	1%	89%	10%	0
C77-5	-1.1	46%	U. Fine	V. C.	M. Well	1%	Opaque Heavies		0	0	0	80%	40%	55%	5%	0
C75-9	-2.4	15%	Med.	Coarse	M. Well	0	--		0	0	0	90%	5%	95%	T%	T%
C76-5	-1.1	28%	Fine	Fine	V. Well	0	Mica		0	0	0	100%	10%	89%	T%	1%
C76-6	-1.4	26%	Fine	VC	Poor	0	Mica		0	0	0	100%	T%	95%	5%	0
C76-8	-2.1	43%	Med.	Granule	V. Poor	T%	Mica		0	0	0	98%	30%	70%	T%	T%
C77-6	-1.4	30%	----	-----	-----	---	--		0	0	0	100%	70%	30%	T%	0
C80-9	-2.4	31%	Fine	VC	Poor	---	--		0	0	0	99%	0	95%	5%	0
C55-3	-2.0	21%	Fine	Coarse	Mod.	0	Opaque Heavies Mica		0	0	0	80%	0	59%	40%	1%
C76-4	-0.8	74%	Fine	Fine	V. Well	0	Mica		0	0	0	100%	60%	39%	T%	1%
C77-5	-1.1	71%	----	-----	-----	---	--		0	0	0	100%	70%	29%	T%	T%
C75-7	-1.8	62%	Med.	Med.	Well	0	--		0	0	0	99%	10%	90%	T%	0
C75-8	-2.1	66%	Med.	Coarse	M. Well	0	--		0	0	0	98%	19%	80%	1%	T%
C55-4	-2.2	24%	L. Med.	V. Coarse	M. Well	2%	Opaque Heavies		0	0	0	20%	20%	80%	T%	T%

TRANSITION SAMPLES - UNIT 2-UNIT 3

C17-4	-2.7	27%	L. Med	V. Coarse	Mod.	3%	Opaque Heavies Mica		0	0	0	35%	0	95%	5%	0
C68-3	-0.2	31%	Fine	Coarse	M. Well	T%	Opaque Heavies		0	0	0	40%	80%	10%	10%	0
C73-4	-0.9	37%	Med.	V. Coarse	M. Well	1%	Opaque Heavies Mica		0	0	0	35%	80%	17%	3%	0
C73-5	-1.2	31%	Med.	V. Coarse	M. Well	T%	Opaque Heavies		0	0	(C)	30%	99%	T%	0	0
C75-10	-2.7	17%	Med.	Granule	Mod.	1%	-- Mica		0	0	0	60%	5%	95%	T%	0
C77-7	-1.7	48%	L. Med.	Granule	V. Poor	1%	--		0	0	0	65%	40%	45%	15%	T%
C85-5	-0.9	33%	Fine	Coarse	M. Well	T%	--		0	0	0	45%	40%	55%	5%	0

^x (C) - Planispirally Coiled

SAMPLE NO.	Sample Depth Meters MSL	Weight % <4φ	COARSE FRACTION (<4φ)												
			INORGANIC MATERIAL						SHELL		PLANT MATERIAL				
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals *	Fragile Shell Hash	Robust Shell Hash	Foraminifera ^x	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates	Wood

UNIT 4 - BROWN FIBROUS PEAT

C71-5	-0.8	0	Med.	Coarse	Mod.	T%	Mica	Fe Agg.	0	0	0	99%	98%	2%	T%	0
C71-9	-1.5	76%	Med.	V. Coarse	M. Poor	0	Fe Agg.	Mica	0	0	0	65%	99%	T%	1%	T%
C72-2	-0.3	92%	V. Fine	Medium	V. Well	T%	Mica	OH.	0	0	0	95%	99%	0	T%	T%
C72-3	-0.5	92%	V. Fine	Coarse	V. Well	T%	Mica	GL.	0	0	0	60%	99%	0	0	T%
C75-2	-0.3	78%	----	-----	-----	--	--	Mica	0	0	0	100%	100%	0	0	0
C77-3	-0.6	95%	Fine	V. Coarse	M. Poor	T%	Mica	GL.	0	0	0	95%	95%	4%	1%	T%
C70-3	-0.3	80%	V. Fine	Fine	V. Well	T%	Mica		0	0	0	40%	99%	T%	T%	0
C85-3	-0.3	99%	Fine	Coarse	Well	0	Fe Agg.	Mica	0	0	0	45%	50%	30%	20%	T%

TRANSITION SAMPLES - UNIT 2-UNIT 4

C67-1	0	17%	Fine	Coarse	M. Well	3%	Opaque Heavies		0	0	0	35%	90%	2%	8%	0
C74-2	-0.2	46%	Fine	Coarse	M. Well	T%	Opaque Heavies	Mica	0	0	(C)	60%	100%	0	T%	0

* Fe Agg. - Iron Aggregates
OH. - Opaque Heavies
GL. - Glauconite

X (C) - Planispirally Coiled

APPENDIX 4

Auxillary Station Sample Data

SAMPLE NO.	Sample Depth Meters MSL	Weight $>4\phi$	COARSE FRACTION ($<4\phi$)												
			INORGANIC MATERIAL						SHELL		PLANT MATERIAL				
			Dominant Grain Size	Maximum Grain Size	Sorting	% Fe Stained	Dominant Non-Quartz Minerals	Secondary Non-Quartz Minerals	Fragile Shell Hash	Robust Shell Hash	Foraminifera	TOTAL VOLUME %	Fine Grassy Fragments	Dark Aggregates	Wood

HIGH ENERGY, IRREGULARLY FLOODED, MAINLAND TYPE BARCKISH MARSH SAMPLES (UNIT 4 BROWN FIBROUS PEAT - SANDY, MUDDY) -- SOUTHERN PAMLICO SOUND

BB-2	0	26%	Fine	Coarse	Well	T%	Opaque Heavies	Mica	0	0	0	35%	99%	1%	0	0
BB-3	0	23%	Fine	Coarse	V. Well	5%	Opaque Heavies		0	0	0	20%	100%	0	0	0

HIGH ENERGY, BAY SHELF SAMPLE (UNIT 2 MUDDY SAND) - SOUTHERN PAMLICO SOUND

BB-1	-1.0	35%	Fine	Coarse	Well	3%	Opaque Heavies	Mica	0	0	0	15%	98%	2%	0	0
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REGULARLY FLOODED, FLOOD TIDE DELTA SHOAL, BARRIER ISLAND TYPE MARSH SAMPLES - OREGON INLET

OI-1	0	66%	Med.	Coarse	M. Poor	6%	Opaque Heavies	Fe Agg.	0	0	0	90%	100%	0	0	0
OI-2	0	8%	Med.	Granular	Mod.	5%	Opaque Heavies		0	0	0	35%	100%	0	0	0

IRREGULARLY FLOODED, MAINLAND, TYPE FRESH MARSH SAMPLE (UNIT 3 DARK AGGREGATE PEAT) - JACOBS CREEK

JC-1	0	40%	V. Fine	Med.	M. Well	T%	Opaque Heavies		0	0	0	95%	20%	80% TX		0
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RELICT, IRREGULARLY FLOODED, MAINLAND TYPE FRESH MARSH SAMPLE (UNIT 3 DARK AGGREGATE PEAT) - LEE CREEK

LC-1	-3.0	65%	Fine	Med.	V. Well	2%	Opaque Heavies		0	0	0	65%	15%	85% TX		0
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Fe Agg. - Iron Aggregates